APPARATUS AND METHOD FOR OPTICAL ADD/DROP MULTIPLEXING

79 24	This application claims is related to Application Serial Number, entitled "Apparatus and Method for Controlling Polarization of An Optical Signal," filed on December, 2000; to Application Serial Number , entitled "Apparatus and Method for Controlling
	Polarization of an Optical Signal, filed on December

TECHNICAL FIELD OF THE INVENTION

The present invention relates to the field of communication systems, and more particularly to an apparatus and method for facilitating optical add/drop multiplexing.





BACKGROUND OF THE INVENTION

Various techniques for facilitating optical add/drop multiplexing have been developed. However, none of the previous approaches has provided a satisfactory solution to the problem of add/drop multiplexing optical signals carrying numerous — sometimes hundreds — of wavelength components. In those situations, the cost of fabricating conventional devices to process each wavelength in the signal quickly becomes prohibitive.

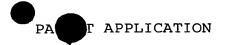
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SUMMARY OF THE INVENTION

The present invention recognizes a need for a method and apparatus operable to economically facilitate add/drop multiplexing, particularly in signals carrying multiple wavelengths.

the invention, aspect of an one In operable to facilitate add/drop multiplexing of optical signals comprises an input operable to receive an input optical signal and an added optical signal, the input operable to generate a first and a second copy of the input signal and a first and a second copy of the added The apparatus further comprises a plurality of at least substantially reflective surfaces, each operable to receive either the first signal copies or the second signal copies and to reflect the copies for ultimate combination at an output to form an output signal for transmission. At least one of the at least substantially reflective surfaces comprises a moveable mirror operable to change its position relative to the input to create a phase shift between the first and second signal copies so that either the input optical signal or the added optical signal is communicated as the output signal depending on the position of the at least one moveable mirror.

In another aspect of the invention, an apparatus operable to facilitate add/drop multiplexing of optical signals comprises a drop phase shift stage operable to receive an input optical signal and to either drop the input signal or to pass the optical signal toward an output, the drop phase shift stage comprising an at least substantially reflective surface operable to change its position to affect whether the input signal is dropped or

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passed to the output. The apparatus further comprises an add phase shift stage operable to receive and communicate as an output either an added signal or the input signal passed from the drop phase shift stage, the add phase shift stage comprising an at least substantially reflective surface operable to change its position to affect whether the added signal or the input signal is passed to the output.

In still another aspect of the invention, a wave division add/drop multiplexer comprises a wavelength division demultiplexer operable to separate an optical input signal into a plurality of wavelengths and an array add/drop multiplexers coupled optical demultiplexer. At least one add/drop multiplexer of the array comprises an input operable to receive an input wavelength signal and an added wavelength signal, and to generate a first and a second copy of the input signal and a first and a second copy of the added signal. The system further comprising a plurality of at least substantially reflective surfaces, each operable receive either the first signal copies or the second signal copies and to reflect the copies for ultimate combination at an output to form an output signal for transmission. At least one of the at least substantially reflective surfaces comprises a moveable mirror operable to change its position relative to the input to create a phase shift between the first and second signal copies so that either the input optical signal or the added optical signal is communicated as the output signal depending on the position of the at least one moveable mirror. The wavelength further comprises a system

multiplexer operable to receive a plurality of output signals from the array of add/drop multiplexers and to multiplex at least some of the output wavelengths into an optical output signal.

In yet another aspect of the invention, 5 division add/drop multiplexer comprises a wavelength division demultiplexer operable to separate an optical input signal into a plurality of wavelengths and an array add/drop multiplexers coupled optical of demultiplexer. At least one of the add/drop multiplexers comprises a micro-electro-optic system (MEMS) including a moveable mirror layer operable to undergo a substantially piston-like motion to a create difference between a wavelength reflected from the moveable mirror layer and a substantial copy of that 15 wavelength, the position of the moveable mirror layer affecting whether the input wavelength is passed through The wavelength division or dropped from the array. add/drop multiplexer further comprises a wavelength division multiplexer operable to receive a plurality of 20 output wavelengths from the array and to multiplex at least some of the output wavelengths into an optical output signal.

In still another aspect of the invention, a wave division add/drop multiplexer comprises a wavelength division demultiplexer operable to separate an optical input signal into a plurality of wavelengths and an array of optical add/drop multiplexers coupled to the demultiplexer. At least one of the add/drop multiplexers comprises a drop phase shift stage operable to receive an input wavelength and to either drop the input wavelength

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or to pass the input wavelength toward an output, at stage comprising an shift phase substantially reflective surface operable to change its position to affect whether the input wavelength is At least one of the dropped or passed to the output. add/drop multiplexers further comprises an add phase shift stage operable to receive and communicate as an output either an added wavelength or the input wavelength passed from the drop phase shift stage, the add phase substantially least stage comprising an at shift reflective surface operable to change its position to added wavelength or affect whether the The wave division wavelength is passed to the output. add/drop multiplexer further comprises a wavelength division multiplexer operable to receive a plurality of output wavelengths from the add phase shift stage and to multiplex at least some of the output wavelengths into an optical output signal.

In another aspect of the invention, a method of facilitating optical add/drop multiplexing comprises 20 receiving an input optical signal and an added optical signal, generating a first and a second copy of the input signal, and generating a first and a second copy of the The method also comprises communicating added signal. the first signal copies toward a first mirror and the 25 copies toward the second mirror, second signal changing the position of the first mirror to create a phase shift between the first and second copy when still further method The combined at an output. comprises communicating either an added signal or the 30

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input signal as an output signal depending at least in part on the position of the first mirror.

In yet another aspect of the invention, a method of facilitating optical add/drop multiplexing comprises receiving an optical input signal at a first stage, generating a first and a second copy of the input signal, and communicating the first signal copy toward a first mirror and the second signal copy toward the second The method further includes changing the mirror. position of the first mirror to create a phase shift between the first and second copy when combined at an output of the first stage and communicating either an added signal or the input signal from the first stage a second stage depending at least in part on the position of the first mirror. In addition, the method comprises generating a first and a second copy of the signal received at the second stage and communicating the first received signal copy toward a third mirror and the second received signal copy toward a fourth mirror. The method still further includes changing the position of the third mirror to create a phase shift between the first and second received signal copies when combined at the second output, and communicating either the added signal or the input signal from the first stage from the second output depending at least in part on the position of the third mirror.

In still another aspect of the invention, a method of facilitating wave division add/drop multiplexing, comprises receiving an optical input signal comprising a plurality of wavelengths, separating the optical signal into a plurality of wavelength signals, and communicating



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at least some of the wavelength signals to an array of optical add/drop multiplexers. At at least one of the add/drop multiplexers, the method comprises receiving an optical signal and an added optical generating a first and a second copy of the input signal, generating a first and a second copy of the added signal, and communicating the first signal copies toward a first mirror and the second signal copies toward the second method further comprises changing the The mirror. position of the first mirror to create a phase shift between the first and second copy when combined at an output, and communicating either an added signal or the input signal as an output signal depending at least in part on the position of the first mirror.

In another aspect of the invention, a method of 15 add/drop multiplexing wave division facilitating comprises receiving an optical input signal comprising a plurality of wavelengths, separating the optical signal into a plurality of wavelength signals, and communicating at least some of the wavelength signals to an array of 20 optical add/drop multiplexers. At at least one of the add/drop multiplexers, the method comprises receiving an optical input signal at a first stage, generating a first and a second copy of the input signal, and communicating the first signal copy toward a first mirror and the 25 second signal copy toward the second mirror. The method further comprises changing the position of the first mirror to create a phase shift between the first and second copy when combined at an output of the first stage, and communicating either an added signal or the 30 input signal from the first stage toward a second

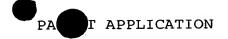
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stage depending at least in part on the position of the the method comprises addition, mirror. In generating a first and a second copy of the signal received at the second stage, communicating the first received signal copy toward a third mirror and the second received signal copy toward a fourth mirror, and changing the position of the third mirror to create a phase shift between the first and second received signal copies when combined at the second output. The method still further comprises communicating either the added signal or the input signal from the first stage from the second output depending at least in part on the position of the third mirror.

Depending on the specific features implemented, embodiments of the present invention may particular 15 exhibit some, none, or all of the following technical One aspect of the invention facilitates advantages. number minimal multiplexing using add/drop components, thereby minimizing the cost of the system. Another aspect of the present invention provides 20 effective and cost efficient mechanism for facilitating optical add/drop multiplexing, particularly in a multiple wavelength optical communication system. In a particular embodiment, implementing MEMS based phase shift stages facilitates fabrication of arrays of these devices at an 25 incremental additional cost to fabricating a single phase This aspect of the invention provides shift stage. significant advantages in facilitating rapid, effective, and economical add/drop multiplexing, particularly in an environment supporting numerous wavelengths. 30





In addition, particular embodiments of the invention allow for bypass of various wavelengths without requiring processing of those wavelengths. This feature can be particularly useful in metropolitan systems, which use some of the multiple wavelengths carried in the optical signals, but perhaps not every wavelength in the signal. This feature, therefore, permits bypassing unused wavelengths to save system resources and expense.

Other technical advantages are readily apparent to one of skill in the art from the attached figures, description, and claims.

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BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention, and for further features and advantages thereof, reference is now made to the following description taken in conjunction with the accompanying drawings, in which:

FIGURE la is a block diagram of an exemplary embodiment of an apparatus operable to provide high speed optical signal processing according to the teachings of the present invention;

FIGURE 1b is a block diagram showing an exemplary geometry associated with one embodiment of an apparatus operable to provide high speed optical signal processing according to the teachings of the present invention;

FIGURES 1c-1d are block diagrams showing other exemplary embodiments of apparatus operable to provide high speed optical signal processing according to the teachings of the present invention;

FIGURES 2a-2d are block diagrams of various embodiments of apparatus operable to provide high speed optical signal processing according to the teachings of the present invention;

FIGURES 3a-3c are block diagrams showing a plurality of views of various embodiments of moveable mirrors operable for use with the apparatus described in FIGURES 1 and 2 and constructed according to the teachings of the present invention;

FIGURE 4 is a block diagram of one embodiment of a variable attenuator constructed according to the teachings of the present invention;





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FIGURE 5a is a block diagram of one embodiment of a one-by-two switch constructed according to the teachings of the present invention;

FIGURE 5b is a block diagram of one embodiment of a two-by-two switch constructed according to the teachings of the present invention;

FIGURE 5c is a block diagram of one embodiment of an n-by-n switch constructed according to the teachings of the present invention;

10 FIGURE 6 is a flowchart showing one example of a method of facilitating optical signal processing according to the teachings of the present invention;

FIGURES 7a-b are block diagrams showing various embodiments of polarization controllers constructed according to the teachings of the present invention;

FIGURE 7c is a graph showing example switching speeds associated with one particular embodiment of the invention;

FIGURES 8a-8h are block diagrams showing various embodiments of systems implementing polarization mode dispersion (PMD) compensators, PMD compensator designs, and components suitable for use in PMD compensators constructed according to the teachings of the present invention;

FIGURE 9 is a flowchart showing one example of a method of controlling the polarization of an optical signal and of mitigating polarization mode dispersion according to the teachings of the present invention;

FIGURES 10a-10b are block diagrams showing a system
and components thereof operable to mitigate polarization
mode dispersion in optical signals having multiple





wavelengths according to the teachings of the present invention;

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FIGURE 11 is a flowchart showing one example of a method of mitigating polarization mode dispersion of optical signals having multiple wavelengths according to the teachings of the present invention;

FIGURE 12 is a block diagram showing an exemplary embodiment of a polarization multiplexing system constructed according to the teachings of the present invention;

FIGURE 13 is a block diagram of an exemplary system operable to facilitate coherent optical communication according to the present invention;

FIGURE 14a is a block diagram of an exemplary embodiment of a multiple channel communication system having gain equalization capabilities constructed according to the teachings of the present invention;

FIGURE 14b is a block diagram of another exemplary embodiment of a multiple channel communication system having gain equalization capabilities constructed according to the teachings of the present invention;

FIGURE 14c is a block diagram of an exemplary gain equalizer suitable for use in a single or multiple band communication system and constructed according to the teachings of the present invention;

FIGURE 15 is a flowchart showing one example of a method of facilitating gain equalization of a plurality of wavelengths according to the teachings of the present invention;

FIGURE 16a is a block diagram showing one embodiment of an exemplary wave division add/drop multiplexer architecture constructed according to the teachings of the present invention;

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FIGURES 16b-16c are block diagrams showing various example embodiments of add/drop multiplexers constructed according to the teachings of the present invention;

FIGURE 16d is a block diagram showing a plurality of add/drop multiplexers as shown in FIGURE 10b arranged to collectively form a wave division add/drop multiplexer according to the teachings of the present invention; and

FIGURE 17 is a flowchart showing one example of a method of facilitating add/drop multiplexing of optical signals according to the teachings of the present invention.

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DETAILED DESCRIPTION OF THE INVENTION

I. Building Blocks for High Speed Optical Signal Processing

FIGURE 1a is a block diagram of one exemplary embodiment of an apparatus 10a operable to provide high speed optical signal processing. Throughout this document, the term "signal processing" includes attenuation, switching, phase shifting, polarization control, mitigation of polarization mode dispersion, or any other manipulation of one or more optical signals.

Apparatus 10a includes a beam splitter 20a, which communicates with mirrors 30a and 40a. Beam splitter 20a may comprise any structure or combination of structures operable to pass a first copy of an optical signal in one direction and a second copy of the optical signal in another direction. For example, in a particular embodiment, beam splitter 20a may comprise a partially silvered mirror. As another example, beam splitter 20a may comprise a mirror having one or more layers of a dielectric coating. As still another example, beam splitter 20a may comprise a fiber coupler.

Throughout this document, the terms "copy" and "signal copy" are used to describe optical signals that are at least substantial copies of the input optical signal, each having at least substantially equal quantities of wavelengths as the other. Depending on the type of beam splitter used to create the multiple signal copies, the two copies may or may not have equal intensities. For example, a 50/50 beam splitter will generate two substantially identical copies of the input signal — substantially equal in content and intensity.

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Other types of beam splitters, however, may create uneven distributions of intensities in the resulting signal "copies." Beam splitters having various ratios other than 50/50 could be used consistent with the present invention. However, an approximately 50/50 beam splitter typically provides a good contrast ratio by maintaining the optical symmetry of a physically symmetrical device.

Apparatus 10a includes a plurality of mirrors, in this case a first mirror 30a and a second mirror 40a. Throughout this document, the term "mirror" refers to an at least substantially reflective surface or collection At least one of mirrors 30a and 40a of surfaces. comprises a moveable at least substantially reflective surface or collection of surfaces. In this example, second mirror 40a comprises a fixed mirror structure. location of second mirror 40a relative to beam splitter 20a does not change during operation of the In this embodiment, first mirror 30a, however, device. comprises a moveable mirror layer of a micro-electrooptic system (MEMS) device operable to be displaced anywhere between positions 32a and 34a. Movement of first mirror 30a can be, for example, in response to a control signal, such as a control voltage. Although this embodiment includes just one moveable mirror, apparatus alternatively comprise additional could 10a Some embodiments of apparatus using multiple mirrors. moving mirrors will be described below.

In the illustrated embodiment, first copy 62a of input optical signal 60a meets first mirror 30a at a grazing angle THETA. In a similar manner, second copy 64a of signal 60a meets second mirror 40a at

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approximately angle THETA. In the example shown in FIGURE THETA comprises approximately forty-five Other grazing angles could be used without degrees. departing from the scope of the invention. In addition, mirrors 30a and 40a could receive first and second signal copies 62a and 64a at different angles from one another without departing from the present invention. Maintaining symmetry between the arms of the device, however, provides an advantage of increasing the contrast ratio at the device's output.

In this particular embodiment, apparatus 10a further includes a beam splitter 50a operable to receive first copy 62a and second copy 64a of input signal 60a, after those signals have been reflected off of mirrors 30a and 40a, respectively. Beam splitter 50a combines components of first copy 62a and second copy 64a of input signal 60a to result in first output signal 72a and second output signal 74a. Beam splitter 50a can be similar in structure and function to beam splitter 20a described above. In some embodiments (described more fully below), beam splitters 20a and 50a could comprise locations on a single beam splitting device.

In the illustrated embodiment, first and second mirrors 30a and 40a are separated from beam splitter 20a by a distance (d). Apparatus 10a can introduce a difference (DELTA d) in signal path (d) by moving first mirror 30a in an at least substantially piston-like motion by a distance DELTA L. Throughout this document, the term "piston-like" motion refers to a motion in which the moveable mirror is intended to be displaced in an approximately parallel plane to the previous mirror

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position. In other words, a "piston-like" motion is intended to substantially maintain the grazing angle THETA between at least a portion of the moveable surface of first mirror 30a and first signal copy 62a. Moving the mirror layer 30a in a substantially piston-like motion to substantially maintain the grazing angle THETA results in an advantage of reducing signal dispersion when the signal copies are combined.

In practice, for various reasons, embodiments of the invention may not exhibit true "piston-like" motion, although such embodiments are intended to be within the scope of the invention. example, the moveable mirror layer may be anchored at its ends and may exhibit some curvature between the anchor points as it moves from one position to another. addition, variances in resistance across the moveable mirror layer may result in one portion of the moveable mirror layer experiencing more movement than another The invention is intended to encompass these portion. embodiments within the definition of "piston-like" motion.

FIGURE 1b is a block diagram showing an exemplary geometry associated with one embodiment of an apparatus operable to provide high speed optical signal processing according to the present invention. Line 32' in FIGURE 1b represents a position of first mirror 30a that would provide a distance (d) between beam splitter 20a and first mirror 30a residing at a first position 32'. Line 32a shows a modified position of first mirror 30a after a piston-like movement resulting in a displacement of DELTA L from position 32a'.

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As shown in FIGURE 1b, moving first mirror 30a from position 32a' to position 32a by distance DELTA L creates a difference of DELTA d in the length of the signal path of first signal copy 62a. This difference in signal path translates to a difference in phase between first signal copy 62a and second signal copy 64a of input signal 60a. The phase difference between first and second copies 62a and 64a results in an interference, which alters the amplitude of output signal 72a relative to that of input signal 60a.

In operation, because first copy 62a of input signal *60a travels a different signal path length than second copy 64a of input signal 60a, a phase difference between the two signal copies results in interference between the two signals when they are combined. For a given change in the signal path length, the amplitude of first output 72a is proportional to \cos^2 of one half of the phase difference PHI between signal copies 62a and 64a. similar manner, for a given change in the signal path amplitude of second output the length, proportional to \sin^2 of one half of the phase difference PHI between signal copies 62a and 64a.

FIGURES 1c and 1d show additional exemplary embodiments of apparatus operable to provide high speed optical signal processing. FIGURE 1c is a block diagram of an apparatus 10b, which operates in a similar manner to apparatus 10a, but uses a single beam splitting device 20b to comprise a first beam splitter operable to separate the input signal 60b into signal copies 62b and 64b, and a second beam splitter operable to combine

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components of the reflected signal copies to form output signals 72b and 74b.

Beam splitter 20b communicates with a plurality of least substantially reflective surfaces including mirrors 30b and 40b. Beam splitter 20b is similar in structure and function to beam splitters 20a and 50a discussed with respect to FIGURE la. As in apparatus 10a apparatus described with respect to FIGURE 1a, includes at least one moveable mirror, in this case first In this example, moving mirror 30b is mirror 30b. similar in structure and function to first mirror 30a in FIGURE la. Apparatus 10b could include additional and/or other moving mirrors without departing from the scope of the invention.

Apparatus 10b also includes mirrors 90b and 80b 15 operable to reflect signal copies 62b and 64b back toward beam splitter 20b, where components of the reflected signals can be combined to form output signals 72b and 74b.

In operation, apparatus 10b receives optical input Beam splitter 20b signal 60b at beam splitter 20b. communicates a first signal copy 62b toward first mirror 30b, and communicates a second signal copy 64b toward First mirror 30b is operable to be second mirror 40b. displaced by a distance DELTA L to create a path length 25 difference DELTA d between the signal path lengths of first signal copy 64a and second signal copy 64b. difference in path length creates a phase difference between the signal copies, which results in a change in amplitude of the signal relative to input signal 60b. 30 selectively varying the position of, for example, first

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mirror 30b, apparatus 10b can control the intensity of output signals 72b and 74b.

FIGURE 1d is a block diagram of another example configuration of an apparatus 10c operable to facilitate high speed optical signal processing. Apparatus 10c operates in a similar manner to apparatus 10a and 10b, but uses a single beam splitter 20c, and orients first and second mirrors 30c and 40c at ninety-degree grazing angles THETA.

Apparatus 10c includes a beam splitter 20c, which communicates with a plurality of at least substantially reflective surfaces including mirrors 30c and 40c. Beam splitter 20c is similar in structure and function to beam splitters 20a and 50a discussed with respect to FIGURE 1a. As in apparatus 10a described with respect to FIGURE 1a, apparatus 10c includes at least one moveable mirror, in this case first mirror 30c. In this example, moving mirror 30c is similar in structure and function to first mirror 30c in FIGURE 1a. Apparatus 10c could include additional and/or other moving mirrors without departing from the scope of the invention.

Apparatus 10c also includes a circulator 65c operable to receive input signal 60c and to communicate that signal to beam splitter 20c, while also receiving output signal 72c and communicating that signal away from the source of input signal 60c.

In operation, apparatus 10c receives optical input signal 60c at beam splitter 20c. Beam splitter 20c communicates a first signal copy 62c toward first mirror 30c, and communicates a second signal copy 64c toward second mirror 40c. First mirror 30c is operable to be

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displaced by a distance DELTA L to create a path length difference DELTA d between the signal path lengths of first signal copy 64a and second signal copy 64b. The difference in path length creates a phase difference between the signal copies, which results in a change in amplitude of the signal relative to input signal 60c. By selectively varying the position of, for example, first mirror 30c, apparatus 10c can control the intensity of output signals 72c and 74c.

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Apparatus 100 shown in FIGURE 2a is similar in structure and function to apparatus 10a shown in FIGURE 1a, but includes moveable mirror elements in each arm of the device. Apparatus 100 includes a first beam splitter 120, which receives an input signal 160 and sends a first signal copy 162 toward a first mirror 130, and a second signal copy 164 toward a second mirror 140. First and second mirrors 130 and 140 reflect first and second signal copies 162 and 164 toward a second beam splitter 150. Second beam splitter 150 combines components of the reflected first and second signal copies 162 and 164 to form first output 172 and second output 174.

In this example, both first mirror 130 and second mirror 140 comprise moveable mirror structures. Each of mirrors 130 and 140 is operable to move relative to the other to contribute to a difference in path length of the

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toward second reflected signals received and splitter 150. Using multiple moving mirrors facilitates the same overall path difference with each mirror moving only a fraction of the distance DELTA L. For example, where the angle THETA is forty five degrees, for a desired total path difference of DELTA d, each of first and second mirrors 130 and 140 moves a distance DELTA L/2, each creating a path difference of DELTA d/2, combining for a total path difference of DELTA d.

As a particular example, first mirror 130 may move away from first beam splitter 120 from position 132 to position 134 to increase the path length of first signal copy 162 by DELTA d/2. Second mirror 140 may move toward first beam splitter 120 from position 144 to position 142 to decrease the path length of second signal copy 164 by The combined effect of the movement of first DELTA d/2. and second mirrors 130 and 140 is to create a total path difference of DELTA d, resulting in a desired phase difference and output intensity.

Implementing multiple moving mirrors provides advantage of decreasing the displacement of each moving in turn, decreases the drive voltage This, mirror. necessary to operate each moving mirror, and increases the speed at which the position of the mirrors, and hence the intensity of the output signal, can be manipulated. 25 Although apparatus 100 is described with respect to the configuration shown in FIGURE 1a, multiple moving mirrors could be similarly be implemented in other embodiments, such as those shown in FIGURES 1c-1d.

Another way to reduce the amount of displacement 30 experienced by each moving mirror for a given level of

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phase difference is to implement additional moving mirrors in each arm of the device. For example, FIGURE 2b shows an apparatus 110 having multiple moveable mirrors on each arm between the first beam splitter 120 and the second beam splitter 150.

Apparatus 110 shown in FIGURE 2b is similar structure and function to apparatus 100 shown in FIGURE 2a and apparatus 105 shown in FIGURE 2a. Apparatus 110 includes a first beam splitter 120, which receives an input signal 160 and sends a first signal copy 162 toward a first mirror 130a, and a second signal copy 164 toward a second mirror 140a. First mirror 130a reflects first signal copy 162 toward a third mirror 130b that, in turn, reflects first signal copy 162 toward a fixed mirror 180 and on to second beam splitter 150. Similarly, second mirror 140a reflects second signal copy 164 toward a fourth mirror 140b that, in turn, reflects second signal copy 164 toward a fixed mirror 190 and on to second beam Second beam splitter 150 combines 150. components of the reflected first and second signal copies 162 and 164 to form first output 172 and second output 174.

In this example, each of mirrors 130a-130b and mirrors 140a-140b comprises a moveable mirror structure. Each of mirrors 130a-130b and 140a-140b is operable to move to contribute to a difference in path length of the signals received and reflected toward second beam splitter 150. In addition, although mirrors 180 and 190 are shown as fixed mirrors, one or more of those mirrors could alternatively comprise moveable mirror structures.

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Using multiple moving mirrors in each arm of device 100 facilitates an overall path difference L with each mirror moving only a fraction of the distance DELTA L. For example, where the angle THETA is forty five degrees, for a desired total path difference of DELTA d, each of first and second mirrors 130 and 140 moves a distance DELTA L/4, each creating a path difference of DELTA d/4, combining for a total path difference of DELTA d.

In a particular example, mirrors 130a-b may move from positions 132 to positions 134 to increase the path length of first signal copy 162 by DELTA d/2. Second mirrors 140a-b may move from positions 144 to positions 142 to decrease the path length of second signal copy 164 by DELTA d/2. The combined effect of the movement of first and second mirrors 130a-b and 140a-b is to create a total path difference of DELTA d, resulting in a desired phase difference and output intensity.

The embodiment shown in FIGURE 2b provides an advantage of further decreasing the necessary displacement of moveable mirrors 130 and 140. This decreases the drive voltage needed to move each mirror and increases the speed of the device. This concept also applies to other embodiments of the invention, including those shown in FIGURES 1c-1d.

Still another way to reduce the amount displacement experienced by each moving mirror while still attaining a given level of phase difference is to reduce the grazing angle (THETA) between signals 162 and first second mirrors 130 and 140, and In a particular embodiment, first and respectively. second beam splitters 120 and 150 form a rhombus with

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first and second mirrors 130 and 140. Referring to FIGURE 1b to illustrate, the path difference DELTA d can be calculated as DELTA d = DELTA L/sin(THETA). Reducing the grazing angle THETA reduces the term sin(THETA), resulting in a greater path difference DELTA d for a given change in mirror location represented by the distance DELTA L.

Apparatus 115 shown in FIGURE 2c is similar in structure and function to apparatus 100 shown in FIGURE 2a, and apparatus 110 shown in FIGURE 2b. Apparatus 115 includes a first beam splitter 120, which receives an input signal 160 and sends a first signal copy 162 toward a first mirror 130, and a second signal copy 164 toward a second mirror 140. First and second mirrors 130 and 140 reflect first and second signal copies 162 and 164 toward a second beam splitter 150. Second beam splitter 150 combines components of the reflected first and second signal copies 162 and 164 to form first output 172 and second output 174.

In this example, both first mirror 130 and second 20 mirror 140 comprise moveable mirror structures. mirrors 130 and 140 is operable to move relative to the other to contribute to a difference in path length of the signals received and reflected toward second beam In the illustrated embodiment, for a splitter 150. 25 desired total path difference of DELTA d, each of first and second mirrors 130 and 140 may move a distance DELTA L, each creating a path difference of DELTA L/sin(THETA), combining for a total path difference of DELTA d. smaller the angle THETA, the larger the path difference 30 created for a given mirror displacement. Said another

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way, using mirrors at small grazing angles to signals 162 and 164, desired path differences can be created with smaller mirror displacements. This results in smaller drive voltages needed to move the mirrors, and faster device operation.

Efficiency and speed advantages can be compounded by implementing combinations of the embodiments shown in FIGURES 2a-2c. For example, a desired phase difference can be introduced between signal copies 162 and 164 using minimal mirror displacement by implementing multiple moving mirrors in each arm of the device, where one or more of the mirrors has grazing angle with the incoming signal that is less than forty five degrees.

FIGURES 3a-3c are block diagrams showing a plurality of views of various embodiments of moveable mirrors 15 suitable for use with the apparatus described in FIGURES 1 and 2. FIGURE 3a is a block diagram showing a movable mirror 130, which can be used in devices shown in FIGURES 2a-2d and describe above. In the particular example shown in FIGURE 3a, movable mirror device 130a comprises 20 a micro-mechanical electro-optical switching ("MEMS") a reflective includes 130a device MEMS device. conducting layer 135a disposed outwardly from an inner conductive layer 131a or 133a. Reflective conducting layer 135a comprises one or more at least substantially 25 reflective structures that are operable to at substantially conduct electricity. Reflective conducting layer 135a, in this embodiment, comprises a layer of metal, such as aluminum, that is substantially reflective of optical signals 162 incident thereon and substantially 30 conductive of electricity. Reflective conducting layer



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135a and inner conductive layer 133a may comprise single layers of one material, or may alternatively comprise multiple layers of one or more materials.

Reflective conducting layer 133a resides outwardly from inner conductive layer 131a and/or 133a. Throughout 5 this document, the term "inner conductive layer" is used to refer to material disposed inwardly from a moveable mirror layer, which is operable to at least substantially conduct electricity. Inner conductive layer 133a may comprise, for example, semiconductor substrate 131a, 10 which has been doped sufficiently to render it at least substantially conductive. In another embodiment, a layer 133a of metal or a layer of doped polysilicon can be formed outwardly from semiconductor substrate 131a, and 133a can comprise the "inner conductive that layer 15 It is not necessary that the inner conductive layer comprise a continuous structure. Inner conductive layer 133 could, for example, comprise a series of electrically coupled strips other (or adjacent discontinuous structures) of material. 20

MEMS device 130a is formed so that a space 137 resides between reflective conducting layer 135a and inner conductive layer 131a (or 133a if used). Various layers interstitial to layers 135 and substrate 131 may be formed for various purposes. Regardless of any other structures formed, however, some amount of space 137 resides between reflective conducting layer 135 and substrate 131, to facilitate reflective conducting layer 135a moving inwardly toward substrate 131a.

30 MEMS device 130 receives optical signals 162 at a grazing angle THETA to reflective conducting layer 135a.

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Reflecting conducting layer 135a reflects a substantial copy of signal 162 away from MEMS device 130a.

Movement of reflective conducting layer 135a toward substrate 131a is accomplished by establishing a voltage differential between reflective conducting layer 135a and substrate 131a or, if used, conductive layer 133a. This voltage differential creates an electrostatic force between the two at least substantially conductive layers, which tends to pull reflective conducting layer 135a toward substrate 131a.

In the illustrated embodiment, reflective conducting layer 135a is biased with a voltage 136, while inner conductive layer 133a is coupled to ground 138. voltage biasing techniques may be used. For example, voltage 136 may be applied to inner conductive layer and reflective conducting layer 135a may As another example, a first voltage may be grounded. applied to reflective conducting layer 135a, while a second voltage, which is different from the first voltage, is applied to inner conductive layer 133a. to establish a biasing scheme operable differential between layers 135a and substrate 131a, or layer 135a and layer 133a (if used), is within the scope of the invention. Of course, semiconductor substrate 131a may itself comprise the "inner conductive layer."

FIGURE 3b is a block diagram of another embodiment of a moving mirror 130b useful, for example, in devices shown in FIGURE 2a-2d. Moving mirror device 130b also comprises a MEMS device. MEMS device 130b includes a substrate 131b, and may also include a conductive layer 133b. Conductive layer 133b is similar in structure and

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function to conductive layer 133a shown in FIGURE 3a. Substrate 131b is similar in structure and function to substrate 131a shown in FIGURE 3a.

MEMS device 130b also includes a plurality of reflective conducting strips 135b. Reflective conducting strips may comprise any material operable to substantially reflect an incident optical signal 162 and to substantially conduct electricity. Reflective conducting strips 135b may comprise, for example, doped polysilicon or a metal, such as aluminum. In addition, inner conductive layer 133b and/or reflective conductive strips 135b may comprise multiple layered structures.

Various structures may be formed interstitial to reflective conducting layer 135b and substrate 131b for accomplishing various functions and results. Regardless of what structures are formed interstitial to layers 135b and substrate 131b, a space 137 is formed between reflective conducting strips 135b and substrate 131b to facilitate movement of reflecting conductive strips 135b toward substrate 131b.

Movement of reflective conducting strips 135b toward substrate 131b is accomplished by establishing a voltage differential between strips 135b and substrate 131b (or conductive layer 133b, if used). As a particular example, strips 135b may be coupled to ground 138, while substrate 131b (or conductive layer 133b) is coupled to a voltage source 136. Again, other methods of creating a voltage differential could be used. For example, strips 135b could be coupled to a voltage source, while substrate 131b (or conductive layer 133b) are coupled to

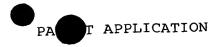
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a ground, or differential voltage sources could be coupled to each of these layers.

FIGURE 3c shows another view of MEMS device 130b. As shown in FIGURE 3, each end of each of strips 135b is In this anchored to, for example, substrate 131b. embodiment, all strips 135b are coupled to the same When a voltage differential voltage potential. created between strips 135b and conductive layer 133b, 135b move toward substrate 131b. strips all embodiment depicted in FIGURES 3b and 3c provides an advantage of controlling air damping during movement of In particular, air strips 135b toward substrate 131b. gaps 139 between strips 135b allow air in space 137 to escape when strips 135b move toward substrate 131b. gaps 139 can be optimally sized to provide adequate control of air damping, while minimizing loss associated with optical signals 162 impinging on strips 135b.

Although the illustrated embodiment shows strips 135b as being elongated rectangular strips, other shapes and configurations could be used without departing from the present invention. In addition, although the illustrated embodiment shows each of strips 135b as being substantially identical to other strips 135b, various of strips 135b could have different dimensions than others without departing from the present invention.

As a particular example of a biasing technique, 130b could be 130a and/or moveable mirror devices implemented in a configuration such as device 105 shown Device 105 could be biased to switch in FIGURE 2b. between a state where moveable mirror elements of mirrors and positions 132 reside at and 140 130

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respectively, to a state where those mirror elements switch to positions 134 and 142, respectively. This switching action would create a longer path length (DELTA d/2) for first signal copy 162 and a shorter path length (DELTA d/2) for second signal copy 164, resulting in a total path difference of DELTA d.

Mirrors 130 and 140 could be biased to accomplish this switching, for example, by applying a control voltage to mirror 140 and no voltage to mirror 130 while device 105 remains in the first state. This would cause mirror 140 to remain in position 144 and mirror 130 to remain in position 132. When switching is desired, device 105 can terminate the control voltage applied to mirror 140, causing the moveable mirror element to return to position 142, and apply a control voltage to mirror 130, causing the moveable mirror element to be drawn to position 134. Other biasing techniques could be used consistent with the present invention.

20 II. Variable Attenuation

One particular aspect of the invention involves a novel variable attenuator and method for providing variable attenuation. FIGURE 4 shows a block diagram of one embodiment of a variable attenuator 200. Variable attenuator 200 is described with reference to a configuration similar to that of apparatus 100 shown in FIGURE 1a. Attenuator 200 could alternatively be constructed using other configurations, such as those shown in FIGURES 1c-1d.

In this example, variable attenuator 200 includes a first beam splitter 220, which receives an input signal

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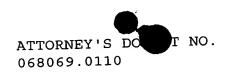
260 and sends a first signal copy 262 toward a first mirror 230, and a second signal copy 264 toward a second mirror 240. First and second mirrors 230 and 240 reflect first and second signal copies 262 and 264 toward a second beam splitter 250. Second beam splitter 250 combines components of the reflected first and second signal copies 262 and 264 to form output signal 272.

One or both of mirrors 230 and 240 can comprise a moveable mirror structure operable to vary its location anywhere between position 232 and position 234 to result in a change in the length of the path of first and/or second signal copies 262 and 264 through attenuator 200. operation, control signals 236 and /or selectively applied to moveable mirrors 230 and/or 240, respectively, to cause one or more of those mirrors to move relative to first and/or second beam splitters 220 and 250. The further mirrors 230 and/or 240 are moved, the higher the degree of phase shift between first and second signal copies 262 and 264. The intensity of output signal 272 is proportional to \cos^2 of one half of the phase difference PHI between first and second signal copies 262 and 264. Therefore, by controlling the amount of movement each mirror 230 and/or 240 experiences, the intensity or attenuation of output signal 272 can be regulated.

Although variable attenuator 200 is shown as having only one mirror 230/240 in each arm of the device, additional mirrors could be implemented in each arm without departing from the scope of the invention. In addition, although grazing angle THETA in FIGURE 4 is shown as approximately forty-five degrees, other grazing

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angles could be implemented consistent with the invention.

III. Optical Switching

In another aspect of the invention, a novel digital switching architecture and methodology is presented. FIGURE 5a shows a block diagram of a one-by-two optical switch 300. In this example, optical switch 300 is similar in structure to variable attenuator 200, which bears similarity to the configuration shown in FIGURE 1a. Optical switch 300 could, however, alternatively be constructed using other configurations, such as those shown in FIGURES 1c-1d.

In the illustrated embodiment, optical switch 300 includes a first beam splitter 320, which receives an input signal 360 and sends a first signal copy 362 toward a first mirror 330, and a second signal copy 364 toward a second mirror 340. First and second mirrors 330 and 340 reflect first and second signal copies 362 and 364 toward a second beam splitter 350. Second beam splitter 350 combines components of the reflected first and second signal copies 362 and 364 to form output signals 372 and 374.

one or both of mirrors 330 and 340 can comprise a moveable mirror structure operable to vary its position to result in a change in the length of the path of and phase difference between first and/or second signal copies 362 and 364. The intensity of first output signal 372 is proportional to cos² of one half of the phase difference PHI between first and second signal copies 362 and 364. The intensity of second output signal 374 is

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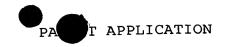
proportional to sin² of one half the phase difference PHI between first and second signal copies 362 and 364. Therefore, when there is no phase difference (or a phase difference of 2-Pi, or an even multiple thereof), first output 372 is at a maximum, while second output 374 is zero, or near zero. When the phase difference equals an odd multiple of Pi, second output 374 is at a maximum, while first output 372 is zero, or near zero. By varying the positions of mirrors 330 and/or 340 to switch between a phase difference of, for example, approximately zero and Pi, optical switch 300 facilitates switching between first output 372 and second output 374.

FIGURE 5b is a block diagram showing one embodiment of a two-by-two switch 310. Two-by-two switch 310 is similar in structure and function to one-by-two switch 300 described with respect to FIGURE 5a, except two-by-two switch 310 receives both a first input 360a (labeled "A1") and a second input 360b (labeled "A2") at beam splitter 320. Of course, optical switch 310 could also be constructed using elements having other configurations, such as those depicted in FIGURES 1c-1d.

In this example, beam splitter 320 sends a copy of each input signal 360a and 360b toward first and second mirrors 330 and 340, which reflect those signal copies toward beam splitter 350. Depending on the position of mirrors 330 and/or 340, switch 310 provides pass through or cross over operation to outputs 372 and 374.

For example, mirrors 330 and/or 340 could be positioned to provide no phase shift between the signal copies of each arm, resulting in pass through operation where input 360a passes through to output 372 and input

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360b passes through to output 374. Alternatively, mirrors 330 and/or 340 could move to provide a phase shift resulting in cross-over operation, where input 360a crosses over to output 374 and input 360b crosses over to output 372. Of course, mirrors 330 and 340 could also be initially positioned to provide cross-over operation in a first state, and pass-through operation when one or more of the mirrors are moved.

of a two-by-two optical switch 400, and optionally added components to enable further switching stages. Elements represented in dashed lines comprise optional elements that can be added to provide additional switching stages. As previously discussed, although optical switch 400 uses a elements similar in configuration to those shown in FIGURE 1a, optical switch 400 could implement elements having alternative configurations, such as those shown in FIGURES 1c-1d.

basic two-by-two embodiment (ignoring the elements shown as coupled by dashed lines), switch 400 20 first optical switch element 405, which includes a receives a first optical signal 460a. Switch 400 further includes a second optical switch element 410, receives a second optical signal 460b. Each of first and second optical switch elements 405 and 410 includes a 25 first beam splitter 420, which receives input signals 460a and 460b, respectively, and sends a first signal copy 462 toward a first mirror 430, and a second signal copy 464 toward a second mirror 440. First and second mirrors 430 and 440 reflect first and second signal 30 copies 462 and 464 toward a second beam splitters 450.

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Second beam splitters 450 combine the reflected first and second signal copies 462 and 464 to form output signals 472a-b and 474a-b.

In the illustrated embodiment, output signals 472b and 474a are communicated toward a beam combiner 456, which combines those signals to create output signal 480. Also in this embodiment, output signals 472a and 474b reflect off of mirror 452 and 454, respectively, toward a beam combiner 458, which combines those signals to create output signal 490. Beam combiners 456 and 458 may comprise any structure or combination of structures operable to receive a plurality of signals and combine those signals into one or more output signals. For example, beam combiners 456 and 458 may each comprise a 50/50 beam splitter.

Some or all of mirrors 430a-b and 440a-b can comprise moveable mirror structures operable to vary their positions to result in changes in the length of the path of and phase difference between first and/or second signal copies 462 and 464. By varying the positions of mirrors 430 and/or 440 to switch between a phase difference of, for example, approximately zero and Pi, each of optical switches 400 facilitates switching between first output 472 and second output 474.

Through appropriate combinations of mirror movements, switch 400 can operate in either pass-through or cross-over mode. For example, mirrors 430a and/or 440a can be operated to create no phase shift between first and second signal copies 462a and 464a, while mirrors 430b and 440b can be manipulated to create no phase difference between first and second signal copies

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262b and 264b. This operation would result in a passthough mode of operation, allowing signals 460a and 460b to pass through to outputs 480 and 490, respectively. particular, in this mode of operation, a zero phase difference between first and second signal copies 462b and 464b results in output 474b being near zero, while output 472b is near a maximum. An approximately Pi phase difference between first signal copy 462a and second signal copy 464a results in output 472a being near a maximum, while output 474a is near zero. Output 480, which is a combination of outputs 472b (maximum) and 474a (zero), therefore, equals output 472b, which corresponds to signal 460b. Output 490, which is a combination of outputs 472a (maximum) and 474b (zero), therefore, equals output 472a, which corresponds to input signal 460a.

As another example, mirrors 430a and/or 440a can be manipulated to create approximately a Pi phase difference between first and second signal copies 462a and 464a, while mirrors 430b and 440b can be operated to create an approximately Pi phase difference between first and second signal copies 262b and 264b. This operation would result in a cross-over mode of operation, causing signal 460a to cross over to output 480, while signal 460b crosses over to output 490.

Although Figure 5c is a block diagram showing one embodiment of a two-by-two switch, additional switching elements could be combined in a similar manner to create an n-by-n optical switch. For example, by implementing components shown in dashed lines in FIGURE 5c and substituting 2x2 switches for beam combiners 456 and 458, switch 400 becomes a four-by-four switch. In that

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embodiment, beam splitter 420a receives input signals 460a and 460d, while beam splitter 420b receives input signals 460b and 460c. In this embodiment, each switch 405 and 410 comprises a two-by-two switch operable to provide either pass through or cross over operation of its input signals 460.

example, where mirrors 430 and 440 are For positioned to create a Pi phase shift facilitating pass through operation, inputs 460a and 460b pass through to outputs 490 and 480, respectively. Likewise, inputs 460c through to outputs 495 and 485, 460d pass Where, however, mirrors 430 and/or 440 respectively. introduce no phase shift, inputs 460a and 460b cross over to outputs 480 and 490, respectively; while inputs 460c and 460d cross over to outputs 485 and 495, respectively.

Although this example shows examples of two-by-two and a four-by-four switches, an n-by-n switch can similarly be constructed from additional combinations of two-by-two switches in a similar manner.

Although switches 300, 310, and 400 are shown as having only one mirror in each arm of the devices, additional mirrors could be implemented in each arm without departing from the scope of the invention.

Moreover, although grazing angle THETA in FIGURES 5a-5c is shown as approximately forty-five degrees, other grazing angles could be implemented consistent with the invention.

FIGURE 6 is a flowchart showing one example of a method 500 of facilitating optical signal processing. Method 500 begins at step 510 where beam splitter 120 (e.g., FIGURE 2b) receives optical signal 160. Beam

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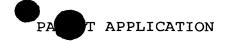
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splitter 120 communicates copies of input signal 160 toward a first mirror and a second mirror at step 515. This may include, for example, a partially silvered mirror receiving input signal 160 and communicating a first signal copy 162 toward first movable mirror 130, and a second signal copy 164 toward second movable mirror 140. First and second mirrors 130 and 140 receive signal copies 162 and 164 at grazing angles other than 90 degrees. In a particular embodiment, mirrors 130 and 140 may receive signal copies 162 and 164 at grazing angles less than 45 degrees. This configuration provides an advantage of minimizing displacement of mirrors 130 and/or 140 to achieve a given signal path difference.

One or more mirrors 130 and/or 140 comprises a MEMS device having a moveable mirror layer that changes its position in a substantially piston-like motion at step 520 to result in a difference in phase between signal copies 162 and 164. This may include, for example, first mirror layer 130 switching from position 132 to position 134, and/or mirror layer 140 switching from position 144 First and second mirrors 130 and 140 to position 142. reflect signal copies 162 and 164, respectively, toward This may include, for example, an output at step 525. first and second mirrors 130 and 140 reflecting signal copies 162 and 164 toward a second beam splitter 150. Alternatively, first and second mirrors 130 and 140 may additional moveable mirror signal copies to elements (see, e.g. FIGURE 2c). Implementing additional moving mirrors in each arm of device 105 provides an advantage of minimizing the displacement of any one of



the movable mirrors while attaining a given signal path difference.

Phase shifted components of first and second signal copies 162 and 164 are combined at step 530 to produce one or more output signals 172 and/or 174. Depending on the level of displacement of mirrors 130 and/or 140, device 105 can operate to provide, for example, phase shifting, variable attenuation, and/or switching functionality on input signal 160.

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IV. Polarization Controllers

FIGURE 7a is a block diagram showing an exemplary embodiment of a polarization controller 610. In this particular embodiment, polarization controller 610 comprises a phase shift-based polarization controller. Rather than requiring physical rotation of the polarization controller, polarization controller 610 uses phase shifts between the principal modes of input signal 616 to orient the output states of polarization.

In the particular example shown in FIGURE 7a, polarization controller 610 includes three stages of phase shifters 620, 622, and 624, each operable assist in translating the input state of polarization to a desired output state of polarization. In this embodiment, first phase shifter 620 couples to a polarization beam splitter receives input optical signal which separates the two principal modes of polarization. Each shifters 620-624 introduces a phase shift between these two principal modes of polarization.

Each phase shifter 620-624 comprises a device or collection of devices operable to introduce a phase shift

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into an optical signal it receives. Phase shifters 620-624 may comprise, for example, micro-electro-mechanical systems (MEMS) comprising moveable mirror elements in each arm facilitating a phase shift between signal copies communicated through each arm. Any device operable to introduce a phase shift into an optical signal, however, may be used.

In this example, beam splitters 626 and 628 couple second phase shifter 622 to first phase shifter 620 and third phase shifter 624, respectively. In one embodiment, at least two phase shift stages share a common beam splitter. The example shown in FIGURE 7a depicts phase shifters 620-624 sharing two common beam splitters 626 and 628. In another embodiment, phase shifters 620-624 could, for example, all share one common beam splitter.

In any case, each of beam splitters 626-628 may comprise, for example, a partially silvered mirror, a mirror having one or more layers of a dielectric coating, or a fiber coupler. In a particular embodiment, each of beam splitters 620-624 comprises an approximately 50/50 beam splitter. While other beam splitter ratios can be used consistent with the scope of the invention, an approximately 50/50 beam splitter maintains the symmetry of the device to provide a good contrast ratio.

In one particular embodiment, beam splitters 626 and 628 may each comprise a mode coupling beam splitter. For example, beam splitters 626 and 628 may include or be coupled to a polarization converter to render beam splitters 626 and 628 mode coupling. This embodiment ensures that polarization controller 610 can convert any

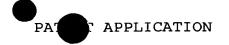
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arbitrary state of polarization (including eigen modes) into any other state of polarization. In addition, this embodiment produces a single output from polarization beam splitter 619, which reduces polarization dependent losses that might otherwise be associated with systems having multiple outputs.

The embodiment of polarization controller 610 shown in FIGURE 7a also includes a polarization beam splitter 619, which receives a phase shifted signal from third phase shifter 624, and aligns the two principal modes of polarization of that signal as desired.

shown in FIGURE 7a provides The embodiment significant advantages over other polarization controller designs, by facilitating reorientation of the principal modes of polarization without requiring the use physical rotation of the compensator, physical squeezing of the fiber communication line, the use of expensive wavequide devices, orthe use lithium niobate additional beam splitter elements due to the presence of bulk wave plates between stages of phase shifters.

FIGURE 7b is a block diagram of one particular controller 610a. a polarization configuration of Polarization controller 610a as shown in FIGURE includes a plurality of phase shifter stages 620-624 each comprising a MEMS-based device, such as the device described above with respect to FIGURE 4. Although each 620-640 has stages a shifter configuration to apparatus 100 shown in FIGURE 2a, phase 620-640 could implement shifter stages configurations, such as those shown in FIGURES 1c-1d.

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In the illustrated example, each phase shifter 620-624 includes two arms 662 and 664, at least one of which comprises a moveable mirror structure 630 and/or 640. Mirrors 630 and/or 640 are operable to move in response to one or more control signals to result in a change in the length of the signal path and, therefore, a phase shift between signal copies communicated through the arms of phase shifters 620-624. Phase shifter stages 620-624 are coupled together by beam splitters 626 and 628. In this example, phase shifter stages 620 and 622 share beam splitter 626, while phase shifter stages 622 and 624 share beam splitter 628.

In this example, polarization beam splitter 618 receives optical input signal 616 and separates the two principal modes of polarization onto a first signal path 662 and a second signal path 664. A polarization beam splitter 619 receives phase shifted signals from third phase shifter stage 624 and aligns the principal modes of polarization with the principal axes of delay line 612.

The heretofore described embodiment of polarization controller 610a succeeds in transforming any input states of polarization that are not eigen modes of the system. For example, s-polarized and p-polarized waves are not other state using transformed into any To facilitate transforming any arbitrary configuration. state of polarization (including eigen modes) into any other state of polarization, FIGURE 7b also shows the optional use of polarization converter 635 to the first phase shift stage (630a/640a) of polarization controller 610a.

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As a particular example, assume that polarization beam splitter 618 operates to reflect the s-polarized p-polarized the transmit and to Polarization converter 635 receives the p-polarized waves and converts them to s-polarized waves, so that beam splitter 628 can combine s-polarized waves coming from first and second arms 662 and 664 and communicate the combined signals toward the second phase shift stage. Although this example shows polarization converter 635 coupled between MEMS device 640a and beam splitter 626, polarization converter 635 could alternatively reside between polarization beam splitter 618 and MEMS device In addition, polarization converter 635 could alternatively reside in first arm 662 of polarization controller 610a.

The polarization controller of FIGURE 7b also shows the optional use of a polarization converter 637 coupled to the last phase shift stage (630c/640c). Polarization converter 637 operates to convert the polarization of the received signal to match that of the signal in the phase shift stage, of the arm opposing splitter 619 will concentrate the polarization beam output into one output signal. Polarization converter 637, can reduce or eliminate polarization dependent losses otherwise associated with the output Although this example shows polarization converter 637 coupled between MEMS device 640c and beam splitter 619, polarization converter 635 could alternatively reside between polarization beam splitter 619 and MEMS device In addition, polarization converter 637 could 640c.

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alternatively reside in first arm 662 of polarization controller 610a.

Polarization converters 635 and 637 may comprise any device or combination of devices operable to flip the polarization of an incoming signal to an orthogonal mode of polarization. Wave plates, Transverse Electrical Transverse Magnetic (TETM) converters, Faraday converters, and mirrors positioned so as to flip the polarization of an incoming signal to a polarization orthogonal to the input state of polarization provide just a few examples of polarization converts suitable for use with this system.

Although FIGURE 7b shows the optional use of a single polarization converter in the first and last phase shift stages, alternatively, a polarization converter could reside in each arm of the first and/or last phase shift stages. In this manner, the physical symmetry of the device can be maintained, so as to increase the contrast ratio of the device. As one particular non-limiting example, where polarization converters are used in each arm of the first and/or last phase shift stage, each polarization converter can comprise a half wave plate -- one oriented at forty-five degrees to the mode axis, the other oriented parallel to the mode axis. Multiple polarization converters in a single phase shift stage may, but need not, be formed from like materials.

FIGURE 7c shows an alternate embodiment of a polarization controller 610b operable to transform any linear input state of polarization to any arbitrary output state of polarization. In this example, polarization controller 610b includes a polarization beam

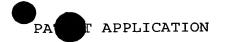
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splitter 658 coupled to at least two substantially reflective surfaces 660 and 670. In a particular embodiment, at least one of the substantially reflective surfaces 660, 670 comprises a MEMS based device operable to undergo a substantially piston like movement to introduce a difference in signal path length and a corresponding difference in phase between a first signal copy 661 and second signal copy 662.

Reflective surfaces 660 and 670 are further coupled to a beam splitter 668, which is still further coupled to at least substantially reflective surfaces 680 and 690. In a particular embodiment, at least one of the substantially reflective surfaces 680, 690 comprises a MEMS based device operable to undergo a substantially piston like movement to introduce a difference in signal path length and a corresponding difference in phase between signal copies received.

splitter operation, polarization beam 658 In receives input optical signal 656 and generates two at least substantial copies of that signal. Polarization beam splitter 658 communicates one copy toward first substantially reflective surface 660 and the other copy toward second substantially reflective surface 67 least one of reflective surfaces 660 and 670, in response to a control signal, changes its position to create a phase difference between the signal copies received at beam splitter 668. Beam splitter 668 receives first and second signal copies 661 and 663, combines components of those signals, and communicates the combined components toward reflective surfaces 680 and 690. At least one of reflective surfaces 680 and/or 690, in response to a

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control signal, changes its position to create a further phase difference between the signal copies received from Reflective surfaces 680 beam splitter 668. reflect the further phase shifted signal copies toward beam splitter 668, which receives the signal copies and combines components of those signals.

Beam splitter 668 then communicates the combined components toward reflective surfaces 660 and 670, which introduce yet a further phase shift between the principal modes, and communicate the further phase shifted modes toward polarization beam splitter 658. Polarization beam splitter 658 communicates a phase shifted output 673 toward a circulator 675, which directs the phase shifted output signal from polarization controller 610b.

As with polarization controller 610a, polarization controller 610b may optionally include a polarization converter 636. Polarization converter 636 operates to facilitate polarization control of eigen modes operates to reduce polarization dependent losses.

Polarization controller 610b includes three stages of phase shift. Reflective surfaces 660 and 670 comprise the first and third phase shift stages, while reflective surfaces 680 and 690 comprise the second phase shift In this example, all phase shift stages share a single beam splitter 668. By sharing one beam splitter 25 between multiple phase shift stages, this embodiment of invention advantageously reduces of number the components required to provide polarization control. For example, this embodiment reduces the number of beam number the reduces also splitters needed, and 30 polarization converters necessary to both process eigen

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modes and reduce or eliminate polarization dependent losses. In addition, this embodiment facilitates implementing a single polarization beam splitting device to serve as both the first (input) polarization beam splitter and the second (output) polarization beam splitter.

Polarization controllers 610a and 610b can be used in a variety of signal processing applications. For example, use in conjunction with polarization sensitive optical components, use in polarization multiplexed lightwave transmission systems, use in coherent communication systems, and use in polarization mode dispersion compensators are just a few examples of applications for polarization controllers 610a and 610b.

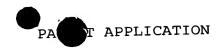
If the characteristic for which the polarization 15 controller is being used changes at a rate that is slower than the reset speed of the polarization controller and, ideally, if the polarization controller can switch at a rate faster than the bit rate of the information being processed, the polarization controller can 20 infinitely rotatable (also known as "reset "endless polarization rotation"). In other words, the polarization controller can be used to provide one phase adjustment along the Poincare Sphere, reset, and provide a second phase adjustment modulo 2Pi from the first phase 25 In this manner, phase shifters 620-624 can adjustment. emulate a single large phase shift using numerous smaller phase shifts between changes in polarization. this technique, polarization controller 610a can simulate an ability to provide a number of rotations on the 30 Poincare Sphere, without actually having the physical

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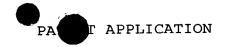
range that would otherwise be necessary to perform the transformation.

One example of a device that is capable of switching at speeds faster than most signals' polarization changes is a MEMS-based phase shifter stage - in particular those operable to undergo substantially piston-like motion and using multiple moving mirror strips to control For example, in mitigating polarization mode damping. dispersion, polarization controller 610a can switch at each milli-second, the than once faster speeds 10 ~ scale on which polarization mode approximate time Therefore, MEMS-based phase shifter dispersion varies. switching at of capable 620-624 stages significantly greater than, for example, once each milliimplemented to provide an endlessly second can be rotatable polarization controller in a PMD compensator

FIGURE 7C is a graph showing realized switching speeds using one particular embodiment of polarization controller 610, which implements MEMS based phase shift stages similar to the device depicted in FIGURE 3a. this example, trace 152 shows a switching of the phase shift stages in response to a control voltage 150. shown in this example, rise times of seven hundred microseconds have been obtained. Other switching speeds may be ascertainable, depending on the processing demands and particular device characteristics utilized. For example, be obtained using an switching speeds can embodiment similar to that shown in FIGURE 3b.

infinitely Another technique for producing an rotatable polarization controller is to implement at least four stages of phase shifters. For example,





although the embodiments shown in FIGURES 7b and 7c include three stages of phase shifters, one or more additional phase shift stages could be cascaded with the illustrated stages to render the controllers endlessly rotatable based on the number of phase shift stages being used. Using four or more stages of phase shifters, for example, allows for resetting one stage of phase shifters, while one or more other stages is processing the signal. This facilitates endless polarization rotation while maintaining lower switching speeds.

FIGURES 8-13 provide various examples of methods and apparatus employing polarization controllers of the present invention. For ease of description, FIGURES 8-13 illustrate various examples using details of polarization controller 610a shown in FIGURE 7b. It should be noted that other embodiments, such as polarization controller 610b shown in FIGURE 7c (or various derivatives thereof) could also be used in the examples given in FIGURES 8-13 without departing from the scope of the invention.

One aspect of the invention provides novel methods and apparatus useful in mitigating polarization mode dispersion (PMD). FIGURES 8a-8h are block diagrams showing various embodiments of systems implementing PMD compensators, PMD compensator designs, and components suitable for use in PMD compensators. FIGURE 8a is a block diagram of an optical communication system 550 implementing a PMD compensator along with one or more margin enhancing elements. As optical communication systems communicate information at higher and higher rates, the need for mitigating polarization mode dispersion increases. In addition, as the bit rate

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increases, so does the need for more system margin. Conventional systems operating at, for example, ten Gigabits per second have implemented margin enhancing techniques, such as distributed Raman amplification, forward-error-correction, and dispersion management. To date, however, no system has emerged which optimizes the location and/or operation of one or more of these margin enhancement techniques in conjunction with mitigation of polarization mode dispersion.

aspect In one of the invention, an optical communication system is presented that optimizes the use of PMD compensators in conjunction with one or more margin enhancing devices. System 550 shown in FIGURE 8a shows an example of one such system. System 550 includes a plurality of fiber spans 551a-551n coupled between an optical source 552 and an optical receiver 568. amplifiers 558a-558n reside between fiber spans 551 to provide amplification of the optical signals traversing those spans. These amplifiers may comprise, for example, erbium doped amplifiers, Raman amplifiers, or any other suitable optical amplifying device.

System 564 also includes a PMD compensator 564 operable to reduce polarization mode dispersion in the optical signals being communicated. In this embodiment, PMD compensator 564 resides somewhere along the fiber span coupling the last in-line filter 558n and receiver 568. System 550 also includes one or more pre-amplifiers 554 coupled to or integral with optical source 552, and one or more post-amplifiers 566 coupled to or integral with optical receiver 568. One or more post-amplifiers

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566 could reside either before the input or after the output of PMD compensator 564.

Coupling PMD compensator 564 at or near the final fiber span provides an advantage of optimizing the optical signal to nose ratio. Placing PMD compensator close to the end of the transmission system results in attenuating both the signal and the noise equally, allowing the system to maintain a good signal-to-noise ratio.

implements 550 system embodiment, this Τn 10 plurality of margin enhancing techniques. For example, system 550 includes a dispersion compensator 556 near the optical source and a dispersion compensator 562 close to This embodiment facilitates prethe optical receiver. postamplification, and line amplification, in 15 dispersion compensation. For amplification dispersion compensators could reside prior to the first amplifications various between stage, amplification stages, and/or after the last amplification stage.

distributed Raman implements example also This 20 In margin. system enhance the to amplification particular, system 550 implements counter-propagating pumps 560a-560n, which help prevent coupling of pump fluctuations to the optical signals being communicated by system 550. Also in this example, system 550 utilizes 25 forward-error-correction circuitry 570 at or accessible to receiver 568.

Although this particular example shows the use of three margin enhancing techniques, the invention does not require each of these techniques. Rather, by implementing a polarization mode dispersion compensator

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and at least one margin enhancing technique, this aspect of the invention provides significant advantages in facilitating optical signal transmission at speeds of, for example, forty Giga-bits per second or more. In addition, by locating the PMD compensator near the optical receiver, system 550 maintains a good signal-to-noise ratio.

FIGURE 8b is a block diagram showing one embodiment including a polarization PMD compensator 600 of controller (PC) coupled to a delay element controlled through control circuitry 614. particular In embodiment, polarization controller 610 may be similar in structure and function to polarization controller 610 PMD compensator 600 operates to shown in FIGURE 7a. reestablish a linear polarization between the various modes of an incoming optical signal 616, by delaying the mode associated with the faster axis of the fiber to result in an equalization in communication speeds of both principal axes.

receives compensator 600 operation, PMD 20 optical signal 616 at polarization controller 610. one embodiment, polarization controller 610 is operable to receive an optical signal having any arbitrary state of polarization and to convert the signal to one having a In another embodiment, linear state of polarization. 25 operates to receive polarization controller 610 optical signal having any arbitrary state of polarization and to convert that signal to one having any other state of polarization. Polarization controller 610 adjusts the state of polarization of each of the principal modes of 30 input signal 616, and passes the adjusted signal to a

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delay element 612, which delays the leading mode and/or speeds up the lagging mode of polarization. The output from delay element 612, or an electrical version thereof, is then fed back to control block 614, which generates control signals for use by polarization controller 610 in continually adjusting the state of polarization of each principal mode.

FIGURE 8c is a block diagram showing one possible embodiment of a polarization controller 610 coupled to a In this particular embodiment, 612. delay element polarization controller 610 comprises a phase shift-based polarization controller comprising at least three stages of phase shifters 620, 622, and 624, each operable to provide one degree of freedom in translating the input state of polarization to a desired output state of In this embodiment, first phase shifter polarization. 620 couples to a polarization beam splitter 618, which receives input optical signal 616 and separates the two principal modes of polarization. Phase shifters 620-624 introduce phase shifts between these two principal modes In the illustrated embodiment, beam of polarization. splitters 626 and 628 couple second phase shifter 622 to first phase shifter 620 and third phase shifter 624, In this example, each of phase shifters respectively. 620-624 shares a common beam splitter 626 or 628. may comprise, for example, shifters 620-624 (MEMS) comprising moveable electro-mechanical systems mirror elements in each arm facilitating a phase shift between signal copies communicated through each arm of the phase shifter, as shown in FIGURES 7b and 7c. Sharing beam splitters between phase shifter stages

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the number of reducing advantage provides an components necessary by eliminating the need for bulk wave plates between each phase shift stage. This reduces fabrication, complexity of device and cost particularly in multiple wavelength applications. embodiment of polarization controller 610b shown FIGURE 7c facilitates sharing a single beam splitter between three stages of phase shifters. The embodiment of polarization controller 610 shown in FIGURE 8c also includes a polarization beam splitter 619, which receives a phase shifted signal from third phase shifter 624, separates the two principal modes of polarization of that signal to ultimately facilitate transmission of the lagging mode of polarization parallel to a faster principal axis of delay element 612, and transmission of the leading mode of polarization parallel to a slower The embodiment principal axis of delay element 612. shown in FIGURE 7c facilitates implementing the first and second polarization beam splitters as a single beam splitting device 658.

Delay element 612 can comprise any hardware, software, firmware, or combination thereof operable to provide a delay to one component of an optical signal with respect to another component of that In a particular embodiment, delay element may length of polarization example, a comprise, for has been intentionally (PMF) that fiber maintaining formed so that one of its principal axes is faster than Where delay element 612 comprises a fixed the other. delay element, polarization controller 610 comprise at least three stages of phase shifters 620-624

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modes of polarization of input signal 616 to the fast and slow axes of fixed delay element 612. Polarization controller 610 could alternatively, however, comprise additional phase shift stages beyond the three shown in FIGURE 7b. Where PMD compensator 600 comprises a fixed delay element 612, polarization controller 610 can comprise any number of phase shift stages greater than two. Additional stages of phase shifters provide an advantage of allowing the use of more simple control algorithms in control block 614.

delay elements used could be typed of Other For example, consistent with the invention. element 612 could comprise one or more retardation plates, or other suitable birefringent material. another embodiment, delay element 612 could comprise a for example, delay line comprising, variable polarization controller coupled between lengths In polarization maintaining fiber. still another could comprise delay element 612 embodiment, electronic delay circuit. Chirped HiBi fiber gratings provide still another example of a element delay applicable to the present invention. For ease description, the following examples will assume use of polarization maintaining fiber as a delay element. delay elements could be used consistent with the invention.

The embodiment shown in FIGURE 8c provides significant advantages over other PMD compensator designs, by mitigating the effects of polarization mode dispersion without requiring the use of physical rotation

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of the compensator, physical squeezing of the fiber communication line, the use of expensive lithium niobate waveguide devices, or the use of bulk wave plates between each stage of phase shifters. Moreover, while this embodiment can be used with a variable delay line, it does not require the use of more expensive variable delay elements. Instead, it facilitates the use of an inexpensive fixed delay element, such as a length of polarization maintaining fiber.

Where polarization controller 610 implements polarization converter coupled to the last phase shift stage, the polarization controller generates a single In that case, a delay element can be coupled directly to the output of the polarization controller. FIGURES 8d-8e are block diagrams showing illustrative examples of coupling delay elements 612a and 612b, respectively, to a polarization controller that does not use a polarization converter to result in a single In FIGURE 8d, delay element 612a comprises a output. fixed delay element including a polarization beam 613 coupled to a length of polarization splitter maintaining fiber 615. In this example, mirrors 607 and 609 reflect the two phase shifted outputs of polarization beam splitter 619 toward polarization beam splitter 613. Polarization beam slitter 613 acts as a signal combiner to form output 617, which is communicated to polarization maintaining fiber 615.

Delay element 612b shown in FIGURE 8e includes a first delay line 621 and a second delay line 623, each coupled to polarization beam splitter 619. In this particular example, each of delay lines 612 and 623

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comprises a length of polarization maintaining fiber. In the illustrated embodiment, polarization beam splitter 619 directs a first phase shifted principal mode of polarization toward first delay line 621, and directs a second phase shifted principal mode of polarization toward a mirror 631, which reflects the second principal mode toward second delay line 623. A mirror 633 receives a delayed phase shifted principal mode from second delay line 623, and directs that signal toward a polarization beam splitter 625. Polarization beam splitter 625 receives the delayed phase shifted principal modes of polarization from delay lines 621 and 623, and combines those signals into a compensated output 627.

The embodiments of delay elements 612a and 612b shown in FIGURES 8d and 8e are intended for illustrative purposes only. Other delay elements and/or configurations of elements could be used without departing from the scope of the invention.

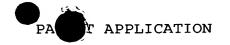
A related aspect of the invention comprises a method and apparatus for facilitating variable delay for use, for example, in a PMD compensator. FIGURE 8f is a block diagram of one embodiment of a variable delay line 700. least 700 comprises at Variable delay line polarization controller 710 coupled between a pair of (PMF) 712a-712b. maintaining fibers polarization Polarization maintaining fibers 712 are similar structure and function to fixed delay element 612 described with respect to FIGURE Polarization 8b. controller 710 is similar in structure and function to polarization controller 610 described with respect to FIGURES 7a and 8a.

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In operation, first polarization maintaining fiber 712 receives an optical signal 705 having its two principal modes of polarization oriented for transmission substantially parallel with the principal axes of first polarization maintaining fiber 712a. First polarization maintaining fiber 712a communicates the lagging mode of polarization of signal 705 parallel to its faster axis, and communicates the leading mode of polarization of signal 705 parallel to its slower axis to generate a partially compensated signal 706.

partially Polarization controller 710 receives compensated signal 708 and performs a phase shift on that signal to align the principal modes with the principal axes of second polarization maintaining fiber 712b. polarization maintaining fiber 712b then Second communicates the leading mode of polarization of signal 708 on its slower principal axis, and communicates the lagging mode of polarization of signal 708 on its slower In this example, a polarization beam principal axis. splitter 713b receives the phase shifted signal from polarization beam splitter 719 of polarization controller facilitates transmission of the 710, and principal mode parallel to the slow axis and the lagging principal mode parallel to the fast axis of polarization maintaining fiber 712b.

By implementing multiple stages of polarization maintaining fiber coupled to a polarization controller, variable delay line 700 facilitates more granular control over compensation than a fixed delay element. To add still more granularity of control, additional stages of

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polarization maintaining fiber separated by additional polarization controllers can be cascaded serially.

FIGURE 8g is a block diagram showing one embodiment of a PMD compensator 750 implementing variable delay line includes a polarization PMD compensator 750 controller 760 coupled to variable delay line 700 and a control block 714. Polarization controller 760 comprises first polarization beam splitter 762 operable receive optical signal 716 and to separate the principal modes of polarization of that signal, and a beam splitter 764 operable to align the principal modes of polarization of the phase shifted signal with the principal axes of variable delay line 780. In the illustrated embodiment, includes just two phase polarization controller 760 shifters 770 and 772 separated by a beam splitter 766. a particular embodiment, beam splitter splitter. 50/50 approximately beam an comprise Implementing a variable delay line, such as variable delay line 700, allows PMD compensator to utilize a two stage phase-shift based polarization controller 760. While additional stages of phase shifters in polarization controller 760 could be used without departing from the scope of the invention, using variable delay line 700 facilitates similar PMD compensation to a three or more polarization controller, shift phase eliminating a stage of phase shifters.

FIGURE 8h is a block diagram showing one possible embodiment of a two-stage phase shift based polarization controller 755 coupled to a variable delay element 780. In this example, each phase shifter stage 770-772 of polarization controller 755 comprises a MEMS-based





device, such as the device described above with respect to FIGURE 4. Although phase shifter stages 770-772 have a similar configurations to apparatus 100 shown in FIGURE 2a, phase shifter stages 770-772 could implement other configurations, such as those shown in FIGURES 1c-1d.

In this example, each phase shifter 770-772 includes two arms, at least one of which comprises a moveable mirror structure 730 and/or 740. Mirrors 730 and/or 740 are operable to move in response to one or more control signals to result in a change in the length of the signal path and, therefore, a phase shift between signal copies communicated through the arms of phase shifters 770-772. Phase shifter stages 720 and 722 share a beam splitter 766 coupled between those stages.

Polarization beam splitter 762 receives optical input signal 716 and separates the two principal modes of polarization onto a first signal path directed toward mirror 730a, and a second signal path directed toward mirror 740a. Each phase shift stage 770 and 772 introduces a phase shift between the principal modes of polarization of signal 716. A beam splitter 764 receives phase shifted signals from second phase shifter stage 772 and aligns the principal modes of polarization with the principal axes of variable delay line 780. Variable delay line 780 may comprise any device or combination of devices operable to provide a tunable delay line.

Using the configuration shown in FIGURE 8h, two stage polarization controller 755 can receive an input signal having any arbitrary state of polarization, and can generate an output signal having a linear state of polarization. Variable delay line 780 can then complete

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the PMD compensation by introducing variable levels of delay into one or more modes of polarization of the phase shifted signal from polarization controller 755. Consequently, the PMD compensator of FIGURE 8h provides efficient and cost effective PMD compensation for signals having any state of polarization.

method 900 of controlling the polarization of a signal and ultimately mitigating polarization mode dispersion. Method 900 begins at step 902 where polarization controller 610 receives optical signal 616 at step 902. Polarization controller 610 separates optical signal 616 into a leading principal mode of polarization and a lagging principal mode of polarization at step 904. This may include, for example, polarization beam splitter 618 receiving optical signal 616, and communicating first mode 662 toward first mirror 630 and communicating second mode 664 toward second mirror 640.

Polarization controller 610 introduces phase shift between the leading and lagging modes of polarization at step 920. This may include, for example, first phase shift stage 620 introducing a first phase shift at step 906, and communicating phase shifted modes 662 and 664 to first beam splitter 626 at step 908. In a particular embodiment, beam splitter 626 may comprise a mode coupling beam splitter operable to flip the polarization of one of the signal copies to facilitate processing of eigen modes.

First beam splitter 626 communicates substantial copies of phase shifted modes toward first and second mirrors 630b and 640b, where a second phase shift is

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introduced at step 912. First and second mirror 630b and 640b communicate the twice phase shifted modes 662 and 664 to second beam splitter 628 at step 914. Second beam splitter 628 receives the twice phase shifted modes and communicates copies of those signals to first and second mirrors 630c and 640c, where a third phase shift is introduced at step 918. In a particular embodiment, second beam splitter 628 may comprise a mode coupling beam splitter operable to flip the polarization of one of the modes, to facilitate communication of a single output signal and reduce polarization dependent losses.

Polarization beam splitter 619 receives phase shifted principal modes of polarization 662 and 664 and separates the principal modes of polarization at step 922. Steps 902 through 922 have described one example of a method of controlling polarization in an optical signal. This method may find application, for example, in a PMD compensator as discussed below, or in a polarization multiplexed lightwave transmission system, in a coherent communication system, or in conjunction with polarization sensitive optical components.

One particular method of mitigating polarization mode dispersion continues at step 924 where polarization controller 610 communicates the phase shifted principal modes of polarization to delay element 612. Although delay element 612 may comprise any of a variety of devices operable to introduce delay, in a particular embodiment, polarization controller 610 aligns the leading mode of polarization with a slow axis of a polarization maintaining fiber 612a at step 926, and aligns the lagging mode of polarization parallel to a

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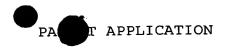
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fast axis of the polarization maintaining fiber 612a at step 928. Using a phase shift based polarization controller, PMD compensator 600 operates to align any arbitrary state of polarization with any other arbitrary state of polarization to result in mitigation of polarization mode dispersion.

FIGURES 10a-10b are block diagrams showing various embodiments of a system and components thereof operable to mitigate polarization mode dispersion in multiplesignals. Where optical wavelength optical comprise multiple wavelengths, each wavelength rotate in polarization differently as it traverses the compensating for Consequently, fiber. optical a be done dispersion must mode polarization wavelength-by-wavelength basis. Conventional solutions PMD compensation that offer endlessly rotatable operation - such as those using lithium niobate based polarization controllers - are very expensive, even on a optical systems single wavelength application. As implement more and more communication channels (using more and more wavelengths), the cost of PMD compensation using conventional equipment quickly becomes prohibitive.

One aspect of the invention provides an architecture that is easily and inexpensively replicated to facilitate arrays of PMD compensators capable of processing any number of wavelengths of light. System 800 as shown in FIGURE 10a includes an array of polarization controllers 810. Each polarization controller in array 810 comprises a MEMS-based phase shift polarization controller. System 800 also includes a delay element 812. Delay element 812 may comprise a fixed delay element, such as polarization

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maintaining fiber 612 shown in FIGURE 8d, or a variable delay element, such as variable delay line 710 shown in the illustrated embodiment, FIGURE 8f. In polarization controllers share a single delay element 812. Alternatively, system 10 could implement multiple 812, elements each servicing one or more delay polarization controllers of array 810.

Where delay element 612 comprises a fixed delay element, each polarization controller of array 810 comprises three or more stages of phase shifters, such as in polarization controller 610 shown in FIGURE 8d. Where delay element 612 comprises a variable delay element such as variable delay line 710 shown in FIGURE 8f, each polarization controller of array 810 may comprise as few as two stages of phase shifters, as in polarization controller 760 shown in FIGURE 8g.

In the illustrated embodiment, system 800 further includes a wavelength division demultiplexer 807 coupled to the output of delay element 812, and an array of detectors 823. Wavelength division multiplexer 807 is operable to receive a compensated signal 817 from delay element 812, separate the various wavelengths of that signal, and pass those wavelengths to a detector 823. Detectors 823 convert the optical signals received into electrical signals for processing in an array of control circuitry 814. Control circuitry 814 generates control signals 821a-821n, which are communicated to associated polarization controllers of array 810.

In an alternative embodiment, demultiplexer 807 and 30 array of detectors 823 could be replaced by a variable filter or a scanning filter operable to sequentially

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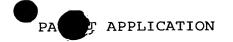
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filter each wavelength from signal 817, and to pass each wavelength to control array 814. Control array 814 could, for example, communicate control signals to array of polarization controllers 810 and also communicate a signal to the scanning filter instructing the filter to deliver the next wavelength.

In operation, wavelength division demultiplexer 802 receives an optical input signal 816 having a plurality of wavelengths, and separates signal 816 into a plurality of individual wavelength signals 806a-806n. embodiment, polarization controllers of array 810 each receive one of wavelengths 806a-806n for processing. Alternatively, system 800 may communicate only some of wavelengths 806 to polarization controller array 810, and allow other wavelengths 806 to bypass polarization controller array 810 through bypass path 823. This may be useful, for example, where system 10 provides PMD compensation for communication systems using only some of the wavelengths of signal 816. In those cases, system 10 can provide efficiencies of compensating only those allowing non-utilized being utilized, wavelengths wavelengths to pass without processing.

Polarization controllers of array 810 receiving utilized wavelengths introduce phase shift into those signals to align the principal modes of polarization to the appropriate axes of delay element 812. Wave division multiplexer 804 receives phase shifted signals 808a-808n from polarization controller array 810, multiplexes those signals into a one or more phase shifted optical signals for communication to delay element 812. Delay element 812 communicates the leading mode of polarization

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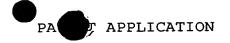
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parallel to its faster axis, and communicates the lagging mode of polarization parallel to its slower axis to mitigate polarization mode dispersion.

Control array 814 receives compensated signals 817 and generates control signals 821 for feedback polarization controllers of array 810. In a particular embodiment, control array 814 comprises an array of electronic circuitry, which receives electronic signals from one or more detectors 823 operable to convert optical signals to electrical signals. Control signals 821 may comprise, for example, voltage signals operable to control the amount of movement in moveable mirror structures, such as 630 and 640 shown in FIGURE 7b or mirrors 730 and 740 shown in FIGURE 8h. Controlling the amount of displacement of these mirrors controls the change in path length of signals communicating with those mirrors and, therefore, the phase shift of the resulting This embodiment provides an advantage of signals. facilitating use of readily available electronic control circuitry for system 800.

FIGURE 10b is a block diagram showing one possible embodiment of polarization controller array 810. Polarization controller array 810 may be useful, for example, in a multiple-wavelength PMD compensator. Alternatively, polarization controller array 810 could be applied to any system where it is desirable to control the polarization of multiple wavelengths in one or more optical signals. Although each polarization controller of array 810 is depicted as similar to polarization controller 610a of FIGURE 7a, polarization controllers 810a-810n could alternatively comprise polarization

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controllers, such as controller 610b shown in FIGURE 7c (or derivatives thereof).

In this example, each polarization controller 810a-810n of array 810 includes a polarization controller similar to that shown in FIGURE 7b. Each phase shifter stage 820a-n through 824a-n (referred to generally as phase shifter stages 820-824) comprises a MEMS-based device, such as the device described above with respect to FIGURE 4. Each phase shifter stage 820-824 includes two arms, at least one of which comprises a moveable mirror structure 630 and/or 640. Mirrors 630 and/or 640 are operable to move in response to one or more control signals 821 to result in a change in the length of the signal path and, therefore, a phase shift between signal copies communicated through the arms of phase shifters Phase shifter stages 820-824 are coupled together by beam splitters 826 and 828. Beam splitters 826-828 may comprise, for example, approximately 50/50 beam splitters. In this example, polarization beam splitter 818 receives various wavelengths 806a-806n of optical input signal 816 and separates the two principal modes of polarization in those signals onto a first signal path and a second signal path. A polarization beam splitter 819 receives phase shifted signals from third phase shifter stages 824 and aligns the principal 25 modes of polarization with the principal axes of delay element 812.

Although the illustrated embodiment shows stages of phase shifters, additional stages could be present invention. implemented consistent with the 30 Moreover, where delay element 812 comprises a variable

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delay line, each polarization controller in array 810 could comprise as few as two stages of phase shifters. Although this example shows just one MEMs device in each arm of each phase shifter stage, additional MEMs devices could be implemented without departing from the invention. Furthermore, although MEMs devices 830 and 840 are shown at an approximately forty-five degree grazing angle, these devices could be located at other grazing angles to the signals being reflected.

Implementing phase shifter based polarization controllers and/or variable delay lines using MEMs devices allows for fabrication of arrays of these devices at an incremental additional cost to fabricating a single compensator. This aspect of the invention provides significant advantages in facilitating rapid, effective, and economical PMD compensation, particularly in a multiple wavelength environment.

method 930 of mitigating polarization mode dispersion in multiple wavelengths of an optical signal. Method 930 begins at step 935 where system 800 receives optical signal 816 having a plurality of constituent wavelengths. System 800 separates optical signal 816 into a plurality of individual wavelength signals at step 940. This may include, for example, wavelength division demultiplexer 802 receiving optical signal 816 and separating optical signal 816 into a plurality of wavelength signals 806a-806n.

System 800 communicates at least some of the wavelengths 806 to array 810 of polarization controllers at step 945. This step may also include, for example,

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diverting one or more wavelengths 806 to a bypass path 823 where those wavelengths 806 are not to be processed by system polarization controllers 810.

Each polarization controller of array 810 separates its associated wavelength 806 into a first and a second principal mode of polarization at step 950. This may include, for example, polarization beam splitter receiving one or more wavelengths 806 and separating their principal modes into wavelengths those polarization. Each polarization controller of array 810 next introduces phase shift between the first and second modes of polarization of each wavelength at step 955. This may include, for example, introducing at least three stages of phase shift between the first and second modes of polarization to align each of the first and second 15 modes with a principal axis of a fixed delay element. Alternatively, this may include introducing at least two stages of phase shift between the first and second modes of polarization to align each of the first and second modes with a principal axis of a variable delay line. 20 addition, polarization converters 635 and 637 could operate to flip polarizations of one of the signal copies, to facilitate processing of, for example, eigen modes, and to reduce polarization dependent losses.

Polarization controllers of array 810 communicate 25 polarization οf modes shifted principal transmission through delay element 812 at step 960. This may include, for example, multiplexing the plurality of wavelength signals 806 into a single optical signal fed to a common delay element 812. Alternatively, this may 30

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include communicating each phase shifted wavelength signal 806 to a separate delay element 812.

modes of polarization principal Communicating comprise further may 812 element delay through determining a control signal based at least in part on an output from delay element 812, and altering the phase shift introduced in array of polarization controllers 810 based on the control signal. In a particular example, optical output 817 may be used as an input to one or more detectors 823, which convert optical signals 817 to electrical signals fed to control array 814. Control array 814, in that embodiment, may comprise electronic circuitry operable to generate electrical control signals 821 to control the amount of phase shift introduced into each wavelength 806. 15

Although array 810 of polarization controllers has been described as being useful in mitigating polarization mode dispersion, a similar array could be applicable to other situations in which it is useful to control polarization of multiple wavelength signals. For example, array 810 is equally suitable for use in sensitive optical polarization with conjunction polarization multiplexed lightwave components, transmission systems, and/or coherent communication systems.

FIGURE 12 is a block diagram showing an exemplary embodiment of a polarization multiplexing system 1800. To meet the ever increasing bandwidth demands of current and future communication systems, optical communication systems often communicate information using multiple wavelengths multiplexed into one or several optical

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Current filter technology often becomes a signals. limiting factor in the number of optical wavelengths that can be communicated in any given signal. For example, a filter at the receiving end of the transmission system should be capable of at least substantially isolating each wavelength carrying information from its neighboring wavelengths. Current filter technology often limits the density of wavelengths that can be packed into any given One way of increasing the density of wave signal. division multiplexed signals is to alternately polarize neighboring wavelengths so that each wavelength polarized orthogonally to its neighboring wavelength. polarization controller can then be used to aid in the filtering at the receiving end of the transmission line neighboring wavelength from its each isolate wavelengths. In this way, polarization controllers can be used to increase the spectral efficiency of the communication system.

System 1800 shown in FIGURE 12 provides another example of an application for an array of polarization controllers useful in controlling the polarization of individual wavelength signals of a wavelength division multiplexed signal. System 1800 includes a first source bank of transmitters 1802 and a second source bank of of banks second First and 1804. transmitters 25 operable any devices transmitters may comprise generate optical signals having different wavelengths. In this example, first source bank 1802 generates odd wavelengths Lamda₁-Lamda_n, while second source bank 1804 generates even wavelengths $Lamda_2$ through $Lamda_{n+1}$. 30 this example, $Lamda_2$ has neighboring wavelengths $Lamda_1$ ATTORNEY'S D 068069.0110 ET NO.

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and Lamda $_3$, and Lamda $_4$ has neighboring wavelengths Lamda $_3$ and Lamda $_5$. First and second source banks 802 and 804 generate neighboring wavelength signals to those generated by the other source bank.

Wavelength division multiplexers 806 and 808 are coupled to first source bank 802 and second source bank 804, respectively. Wavelength division multiplexers 1806 and 1808 each multiplex the individual wavelength signals received into a multiple wavelength signal 1812 and 1814, respectively.

a polarization includes 1800 also System splitter 1816, which receives multiple wavelength signals 1812 and 1814, and orthogonally polarizes those signals for transmission over the principle modes of polarization optical communication link 1820. communication link 1820 may comprise a number of lengths of optical fiber, and may include one or more amplifier stages 1822a-1822n as pre-amplifiers, post-amplifiers, and/or inline amplifiers to communication link 1820. division wave includes а further 1800 System demultiplexer 1824 coupled to optical communication link Wave division demultiplexer 1824 receivés multiple wavelength signals 1812 and 1814 communicated over the principle modes of polarization of communication link 1820, and separates the individual wavelength signals. In a particular embodiment, System 1800 may include Filters 1826 operate to at least filters 1826a-1826n. substantially isolate the desired wavelength signal from System 1800 also its neighboring wavelength signals. includes an array of polarization controllers 1810. Each polarization controller of array 1810 operates to provide

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any necessary adjustment to the state of polarization of facilitate incoming signal wavelength to polarization selection element separating the neighboring orthogonally polarized wavelengths.

In a particular embodiment, array 1810 is similar in structure and function to array 810 described in FIGURE array 1810 Each polarization controller of 10b. comprises a plurality of phase shift stages, where at least one of the phase shift stages shares a beam splitter with another of the phase shift stages, such as in polarization controller 610a shown in FIGURE 7b. one particular embodiment, each polarization controller of array 1810 may comprise three phase shift stages, where all phase shift stages share a common splitter, such as in polarization controller 610b shown 15 in FIGURE 7c.

In one particular example, each of the phase shift stages may, for example, include MEMS-based devices, such as those shown in FIGURES 3a-3c, operable to undergo a substantially piston-like motion to introduce a phase shift between copies of the optical signal being phase Each polarization controller of array 1810 shifted. to control polarization of one wavelength operates implementing an array of polarization By signal. controllers, such as shown in FIGURE 10b, the invention facilitates processing of densely packed wavelengths at a small incremental cost over the cost of processing a single wavelength.

In addition, system 1800 includes a plurality of 1828a-1828n. polarization selection elements 30 selection particular embodiment, each polarization

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element may comprise, for example, a polarization beam splitter or a polarizer. Polarization selection elements 1828 operate to separate the desired signal wavelength from its orthogonally polarized neighboring wavelengths.

1830 System 1800 also includes array an Array of detectors 1830 operates to receive detectors. optical signals from polarization selection elements 1828 and to form electrical signals 1834a-1834n, which can be circuitry. fed to array 1832 of control example, may comprise, for 1832 array circuitry electronic control circuitry operable to receive feedback signals from polarization selection elements 1428 and to generate control signals 1836a-1836n operable to effect polarization controllers 1810. adjustment οf wavelength individual 1840a-1840n receive Receivers 15 signals from polarization selection elements 1828.

In operation, system 1810 generates a plurality of neighboring wavelength signals at one or more source banks 1802, 1804, and communicates those signals to two or more wavelength division multiplexers 1806, Each wavelength division multiplexer 1806, 1808 receives a plurality of wavelength signals and multiplexes those signals into a multiple wavelength optical signal 1812, 1814, respectively.

the receives splitter 1816 Polarization beam 25 multiple wavelength optical signals and communicates each signal along a separate principle mode of polarization of an optical fiber 1820. Wavelength division demultiplexer the multiple wavelength signals receives separates the individual wavelength signals therefrom. 30

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Each polarization controller of array 1810 of polarization controllers receives one of the wavelength signals and adjusts the state of polarization of that wavelength signal to assist in separating that wavelength signal from its neighboring wavelength signals. Filters 1826 and polarization selection elements 1828 at least substantially isolate the individual wavelength signal from any remnants of neighboring wavelength signals, and communicate the individual wavelength signals to receivers 1840.

Control array 1832 receives input from polarization selection elements 1828 and generates control signals 1836, which are communicated to polarization controllers of array 1810. These control signals facilitate adjustment of the state of polarization of the incoming wavelength signals to ensure that those signals can be identified distinctly from neighboring wavelength signals.

FIGURE 13 is a block diagram of an exemplary system coherent facilitate operable to 1900 20 communication. Coherent optical communication typically involves combining an optical signal carrying desired information (an incident signal) with a higher power signal from a local oscillator to create a cross product of the two signals, which is of higher power than the 25 incident signal. By substantially matching the phases of the incident signal with the local oscillator signal, the power of the cross product can be maximized and made significantly larger in magnitude than the incident signal. The cross product portion of the signal is more 30 the incident signal, thus than easily detectable

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increasing the sensitivity of the optical system and increasing the system's tolerance to noise.

The equation below mathematically illustrates the operation of a coherent optical system, such as system 1900.

$$I_{ph} = R[P_{inc} + P_{loc} + 2(P_{inc}P_{loc})^{\frac{1}{2}} cos(w_{inc}t - w_{loc}t)]$$

In this equation, I_{ph} is the intensity of the combined the photo-detector; R signal received at responsibility of the photo-detector; $P_{\rm inc}$ is the power of the incident signal; and P_{loc} is the power of the local oscillator signal. Because the local oscillator signal is known, it can easily be filtered from the output signal. By using a local oscillator signal having a power that is significantly larger than the power of the incoming signal, the cross product term of this equation - assuming the incident signal and local oscillator signal have substantially equal polarizations - will overwhelm the power of the incident signal, such that the 20 incident signal can be ignored compared to the cross product.

Because the polarization of the incident signal can is desirable to implement a vary over time, it polarization controller to ensure that the incident is not orthogonally polarized to the local oscillator signal. Thus, coherent optical communication systems provide another application for polarization controllers.

System 1900 shown in FIGURE 13 illustrates a generic 30 example of a system for providing coherent optical

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This example shows an embodiment of a communication. facilitate coherent optical to operable communication of multiple wavelength signals 1902a-1902n $(Lamda_1-Lamda_n)$. System 1900 includes an optical mixer each wavelength signal 1902a-1902n. 1906 for optical mixer receives an incident wavelength signal 1902 from a wavelength division demultiplexer 1903, and a local oscillator signal 1904 from a local oscillator 1912. Optical mixers 1906 combine incident wavelength signals 1902 with local oscillator signals 1904, 10 communicate the combined signal to a photo-detector 1908. Local oscillators 1912 reside in feedback loops 1920 between photo-detectors 1908 and optical mixers 1906.

Coherent system 1900 may comprise a homodyne or a heterodyne system. In a homodyne system, the frequencies of the incident signal and the local oscillator signal are approximately equal. In that case, the output of difference phase the carries photo-detector 1908 and the signal information of the incident oscillator signal. Where coherent system 1900 comprises 20 a homodyne system, local oscillator may be preceded by, for example a loop filter operable to generate an output In addition, these that drives the local oscillator. systems may implement an isolator downstream from the local oscillator to ensure that optical signals are not 25 fed back to the local oscillator.

Heterodyne systems are those in which the frequency of the incident signal and the local oscillator signal differ by a frequency generally referred to as the systems Heterodyne "intermediate frequency." implement, for example, an intermediate frequency filter

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between the photo-detector and the local oscillator. The output of the intermediate frequency filter is used to drive an automatic frequency controller coupled between the intermediate frequency filter and the local oscillator. The automatic frequency controller generates an output that is proportional to the difference of the frequency of the intermediate frequency filter output and a desired intermediate frequency value. This signal can be used to maintain the frequency difference between the local oscillator output and the received signal.

To help ensure that the incident wavelength signals 1902 and the local oscillator signals 1904 are not orthogonally polarized, system 1900 includes at least one polarization controller for each wavelength signal 1902 being processed. In the illustrated embodiment, an array 1910 of polarization controllers may reside within feedback loop 1920 to adjust the state of polarization of the local oscillator signals 1904 relative to the incident wavelength signals 1902. Alternatively, or in addition, an array 1910 of polarization controllers could reside in line with incident wavelength signals 1902, to facilitate adjustment of the state of polarization of those signals relative to the local oscillator signals 1904.

25 In operation, system 1900 receives incident optical wavelength signals at optical mixers 1906, and combines those signals with optical signals 1904 generated by local oscillators 1912. Optical mixers 1906 communicate combined signals to photo-detectors 1908, which generate electrical equivalents of the optical signals received. A control signal derived from the outputs from photo-

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detectors 1908 is communicated through feedback loops 1920 to local oscillators 1912 and/or control circuitry coupled thereto. Local oscillators 1912 generate local oscillator signals 1904 in response to the outputs of photo-detectors 1908.

array 1910 embodiment, particular In polarization controllers is coupled to local oscillators Each polarization controller of array 1910 includes, or is coupled to control circuitry operable to state the needed to adjustment determine an polarization of the local oscillator signal 1904 to incident wavelength 1902 signal ensure that polarized orthogonally to local oscillator signal 1904. Polarization controllers of array 1910 can then adjust the state of polarization of the local oscillator signals 1904 to more closely align with the state of polarization of the corresponding incident wavelength signals 1902. As discussed above, array 1910 could alternatively, or in addition reside in line with incident wavelength signals 1902 and operate to adjust the state of polarization of those signals.

Each array of polarization controllers could be similar in structure and function to array 810 shown in FIGURE 10b. In that embodiment, each polarization controller of array 1910 comprises a plurality of phase shift stages, where at least one of the phase shift stages shares a beam splitter with another of the phase shift stages, such as in polarization controller 610a shown in FIGURE 7b. In one particular embodiment, each polarization controller of array 1810 may comprise three phase shift stages, where all phase shift stages share a

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common beam splitter, such as in polarization controller 610b shown in FIGURE 7c. System 1900 may be particular well suited to this type of polarization controller, since the state of polarization of the local oscillator

In one particular example, each of the phase shift stages may, for example, include MEMS-based devices, such as those shown in FIGURES 3a-3c, operable to undergo a substantially piston-like motion to introduce a phase shift between copies of the optical signal being phase shifted. By implementing an array of polarization controllers, such as shown in FIGURE 10b, the invention facilitates processing of multiple wavelengths at a small incremental cost over the cost of processing a single wavelength.

V. Gain Equalization in Multiple-Wavelength Optical Signals

FIGURE 14a is a block diagram of an exemplary embodiment of a multiple channel communication system 1000 having gain equalization capabilities. Existing band have used the conventional ("C") wavelengths to communicate optical signals. for bandwidth, the capacity demand increasing communication systems is being expanded by the addition System 1000 utilizes not of new communication bands. only the C-band 1012 of wavelengths, but also the long wavelength ("L") band 1024 and the short wavelength ("S") In this embodiment, each band 1012-1016 is band 1026. approximately 40 nanometers wide. Other bandwidths could be utilized consistent with the invention.

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System 1000 includes an optical fiber 1010 operable to communicate a plurality of wavelength bands 1012, 1014, and 1016. In the illustrated embodiment, each band 1012-1016 is amplified using one of optical amplifiers 1022-1026, respectively. Optical amplifiers 1022-1026 may comprise, for example, thulium-doped amplifiers, Raman amplifiers, and/or rare-earth doped amplifiers, such as erbium-doped amplifiers.

As additional bands are added to a communication system, the net power of the fiber is increased. when multiple invention recognizes that wavelength are communicated using a single system, longer wavelength signals tend to rob energy from shorter wavelength signals. As a consequence, it is desirable to introduce additional attenuation for longer wavelength 15 signals to compensate for the introduced gain tilt. System 1000 addresses this need by including a gain equalizer 1030, which comprises a device operable to provide variable attenuation to one or more selected wavelengths. 20

In a particular embodiment, a single gain equalizer 1030 is coupled to the outputs of a plurality of amplifiers 1012-1016 in parallel. System 1000 provides an advantage of compensating for gain tilt in a multiple channel system, while maintaining an acceptable signal to noise ratio. By coupling gain equalizer 1030 to the output side of amplifiers 1012-1016, system 1000 avoids attenuating the inputs to amplifiers 1012-1016, which would degrade the signal to noise ratio.

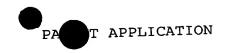
In operation, system 1000 receives optical signal 30 1010 comprising a plurality of wavelength bands 1012-

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through a respective optical amplifier 1022-1026, where the optical signals are amplified. Gain equalizer 1030 receives amplified optical signals from amplifiers 1022-1026, and attenuates the signals on a per wavelength basis. In a particular embodiment, gain equalizer 1030 attenuates longer wavelength signals more than shorter wavelength signals to adjust for a gain tilt caused by the longer wavelength signals robbing energy from shorter wavelength signals.

FIGURE 14b is a block diagram of another exemplary embodiment of a multi-channel communication system 1100 having gain equalization capabilities. System includes an optical fiber 1110 operable to communicate a plurality of wavelength bands 1112, 1114, and 1116. the illustrated embodiment, each band 1112-1116 amplified using one of multiple stage optical amplifiers Each optical amplifier 1122-1122-1126, respectively. 1126 comprises a plurality of stages; in this example two Each amplifier 1122-1126 may comprise, for stages. amplifiers, thulium-doped amplifiers, Raman example, and/or rare-earth doped amplifiers, such as erbium-doped amplifiers.

In the illustrated embodiment, system 1100 includes gain amplifiers 1030a-1030c coupled intermediate two 25 stages of each of the multi-stage amplifiers 1022-1026. Implementing a gain equalizer for each of the bands 1112 provides an advantage of facilitating optimization of range narrow more equalizer for a gain wavelengths. Moreover, coupling gain equalizers between 30 multi-stage amplifiers provides the stages of

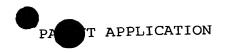
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advantage of maintaining an acceptable optical signal-tonoise ratio, while reducing the risk of saturating optical amplifiers.

FIGURE 14c is a block diagram of one example of a gain equalizer 1200 suitable for use in a single band communication system or a multiple band communication gain equalizer embodiment, this In system. comprises a phase-shift based gain equalizer operable to provide variable gain or attenuation on a per-wavelength basis by introducing interference between two instances of the optical signal. Gain equalizer 1200 includes a wavelength demultiplexer 1280 operable to receive optical signal 1260 and to separate optical signal 1260 into a plurality of wavelengths 1260a-1260n. Gain equalizer 1200 further includes a wavelength multiplexer 1290 operable to receive processed versions of wavelengths 1260a-n and to multiplex those wavelengths into one or more optical output signals 1272.

signal optical input cases, some comprise wavelengths that need not be processed by gain particular embodiments, In 1200. equalizer equalizer 1200 includes a bypass 1275 coupled between Bypass 1275 demultiplexer 1280 and multiplexer 1290. facilitates communication of selected wavelengths between demultiplexer 1280 and multiplexer 1290 without the need equalizer 1200, Gain signals. process those therefore, provides an advantage in systems, such as may use multiple metro communication systems, which but not require processing all of wavelengths, wavelengths all of the time. 30

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In this example, gain equalizer 1200 comprises a plurality of phase shift stages, each operable to receive one wavelength 1260 and to introduce attenuation or gain into that wavelength depending on a phase shift operating on that signal 1260. Although the phase shift stages shown in FIGURE 14c have a similar configuration to those in FIGURE 2a, other configurations could implemented, such as those shown in FIGURES 1c-1d.

In this example, each phase shift stage receives from a first beam splitter 1220a a first copy 1262 and a second copy 1264 of its associated wavelength 1260. phase shift stage includes at least a first mirror 1230 and a second mirror 1240, operable to receive the first and second signal copies 1262 and 1264, respectively.

At least one of first and second mirrors 1230 and 1240 comprises a moveable mirror operable to change its position relative to first beam splitter 1220 to create a change in the length of the signal path traveled by first signal copy 1262 relative to the length of the signal path traveled by second signal copy 1264. This change in signal path length corresponds to a phase shift between the two signal copies, which results in an interference when the signal copies are combined at a second beam splitter 1250. System 1200 may implement any moveable mirror structure, such as one of the moveable mirror structures described with respect to FIGURES 3a-3c. controlling the amount and direction that each mirror 1230 and/or 1240 is moved, system 1200 facilitates variable gain or attenuation of each wavelength 1260a-1260n of signal 1260. 30

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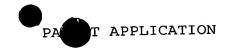
(MEMS) micro-electro-optic system Using mirrors, such as those described with respect to FIGURES 3a-3c, provides an advantage of facilitating large scale replication of each phase shift stage. For example, each plurality of first mirrors 1230 could be simultaneously semiconductor substrate single a formed on Likewise, each plurality of second mirrors 1240 could be semiconductor single а formed on simultaneously therefore, the invention, One aspect of substrate. facilitates construction of gain equalizers capable of processing numerous wavelengths for a small incremental This aspect of cost over a single stage of attenuators. invention provides significant cost savings in signals carrying information on multiple processing channels or wavelengths.

FIGURE 15 is a flowchart showing one example of a method 1300 of facilitating gain equalization of an optical signal having a plurality of wavelengths. method 1300 begins at step 1310 where gain equalizer 1200 receives optical signal 1260 and separates wavelengths 1260a-1260n at step 1320. This may include, for example, demultiplexing input signal 1260 into its constituent wavelengths.

Gain equalizer 1200 may bypass wavelengths that do be processed by communicating need to Other wavelengths are wavelengths over bypass 1275. communicated to one or more first beam splitters 1220 of each attenuator of equalizer 1200 at step 1330. Beam splitters 1220 of each attenuator communicate a first copy of the input wavelength 1262 toward first mirrors 30 1230 at step 1350, and communicate a second copy 1264

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In this example, at least toward second mirrors 1240. one of first mirror 1230 and second mirror 1240 comprises a MEMS device having a moveable mirror layer operable to move in an at least substantially piston-like motion relative to a semiconductor substrate. One or more MEMS devices 1230 and/or 1240 receive control signals at step 1360 causing their respective moveable mirror layers piston-like substantially least an at undergo movement, changing the moveable mirror layer's location First and second with respect to beam splitter 1220. mirrors 1230 and 1240 reflect wavelength signal copies 1262 and 1264 toward an output at step 1370. The output may comprise, for example, beam splitter 1250. In other embodiments, beam splitter 1220 may comprise the input and the output to the attenuator.

In any case, components of the wavelength signal copies are combined at step 1380 to generate an output wavelength signal that varies in amplitude from the input wavelength signal 1260 due to a phase shift caused by the piston-like movement of one or more moveable mirror layers of mirrors 1230 and/or 1240.

VI. Optical Add/Drop Multiplexing

of an exemplary system 1400 operable to perform wave division add/drop multiplexing. System 1400 includes a wave division demultiplexer 1410 operable to receive an optical signal 1460 and to separate optical signal 1460 into a plurality of wavelengths 1460a-1460n. System 1400 further includes a wavelength multiplexer 1490 operable to receive processed versions of wavelengths 1460a-n and

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to multiplex those wavelengths into one or more optical output signals 1472.

System 1400 further comprises an array 1445 of MEMSbased optical add/drop multiplexers, each operable to facilitate add/drop multiplexing of one of wavelengths In a particular embodiment, MEMS array 1445 may mirror moveable array of MEMS having comprise an structures operable to be displaced in an at least to create an motion piston-like substantially substantial copies the interference between two wavelength signal. Implementing array 1445 using MEMSwave-division facilitates arrays multiplexing on any number of wavelengths 1460a-n at a facilitating add/drop over incremental cost small multiplexing for a single wavelength signal. result, system 1400 provides a cost effective mechanism for wave-division add/drop multiplexing large numbers of wavelengths.

signal input cases, optical some In comprise wavelengths that need not be processed by array In particular embodiments, system 1400 includes a 1475 coupled between demultiplexer 1410 Bypass 1475 facilitates communication multiplexer 1490. of selected wavelengths between demultiplexer 1410 and 1490 without the need to process those multiplexer signals. System 1400, therefore, provides an advantage in systems, such as metro communication systems, which may use multiple wavelengths, but not require processing of all wavelengths all of the time.

In operation, system 1400 receives input signal 1460 and demultiplexes that signal into a plurality of

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Some of wavelengths wavelength signals 1460a-1460n. 1460a-n may be routed over bypass 1475, while others are MEMS-based add/drop of array 1445 directed toward MEMS-based add/drop multiplexers receive multiplexers. wavelengths 1460a-n and may drop the received wavelength in favor of an added wavelength signal to replace the Processed wavelengths 1460a-n and dropped wavelength. combined then 1460a-n are bypassed wavelengths wavelength division multiplexer 1490 and communicated as output signal 1472.

FIGURE 16b is a block diagram showing one particular example of a MEMS-based add/drop multiplexer (ADM) 1405. In the illustrated embodiment, ADM 1405 is similar in structure and operation to two-by-two switch 310 shown in FIGURE 5b. The invention is equally applicable to other configurations, such as that shown in FIGURE 1c.

ADM 1405 includes a first beam splitter 1420, which receives both an input optical signal 1461, as well as an added signal 1465. Beam splitter 1420 generates a first copy and a second copy of both input signal 1461 and ADM 1405 communicates the first added signal 1465. copies along a first signal path 1462 and the second copies along a second signal path 1464. A first mirror 1430 receives first signal copies from signal path 1462 and reflects those signal copies toward an output, in A second mirror this case second beam splitter 1450. 1440 receives second signal copies from signal path 1464 and reflects those signal copies toward an output, this case second beam splitter 1450. The reflected first and second signal copies are combined at the output, in this case a second beam splitter 1450.

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By changing the position of one or more of mirrors 1430 and 1440 residing between the input and the output of the phase shifter, a phase shift is introduced and second signal copies. Ву first between the introducing a particular phase shift, 1405 ADM facilitate pass through operation, or add/drop operation. In a pass through mode of operation, ADM 1405 operates to communicate input signal 1461 to an output 1472 for In an add/drop mode, ADM 1405 further transmission. operates to drop input signal 1461 at drop output 1474, and to communicate added signal 1465 to output 1472 for transmission in lieu of input signal 1461.

Some or all of mirrors 1430 and 1440 can comprise structures operable to vary mirror moveable positions to result in a change in the length of the path and phase difference between first and/or second signal copies communicated along signal paths 1462 and 1464. For example, the intensity of transmitted output signal 1472 is proportional to \cos^2 of one half of the phase difference between first and second signal copies of the input signal 1461, and the \sin^2 of one half of the phase difference between the first and second copies of Likewise, the intensity of dropped added signal 1465. output signal 1474 is proportional to \sin^2 of one half of the phase difference between first and second signal copies of the input signal 1461, and the cos² of one half of the phase difference between the first and second copies of added signal 1465.

Therefore, when there is no phase difference (or a phase difference of 2Pi, or an even multiple thereof) input signal 1461 is communicated as transmitted output

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Where there is a Pi (or odd multiple of Pi) phase difference,, input signal 1461 is dropped at drop output is communicated over added signal 1465 and transmitted output 1472. By varying the positions of mirrors 1430 and/or 1440 to switch between a phase difference of, for example, approximately zero and Pi, ADM 1405 facilitates either passing input signal 1461 through to transmitted output 1472, or dropping input 1465 signal added of 1461 in favor signal transmission over transmitted output 1472.

Although the illustrated embodiment shows just one MEMs device in each arm of the phase shifter, additional MEMs devices could be implemented without departing from the invention. Furthermore, although MEMs devices 1430 and 1440 are shown at an approximately forty-five degree grazing angle, these devices could be located at other grazing angles to the signals being reflected.

FIGURE 16c is a block diagram showing another example of a MEMS-based add/drop multiplexer (ADM) 1500. In the illustrated embodiment, ADM 1500 includes a drop phase shift stage 1505 that is separate from an add phase shift stage 1510. This embodiment may be particularly useful, for example, where it is desired to reduce or eliminate interference between input and added signals that would otherwise traverse the same phase shift stage.

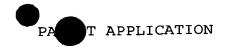
In this example, drop phase shift stage 1505 receives an optical input signal 1560 and operates to either communicate signal 1560 to add phase shift stage 1510, or to drop signal 1560 from the circuit. Add phase shift stage 1510 operates to either input signal 1560 from drop phase shift stage 1505 or to receive an added

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optical signal 1565, and to communicate the received signal to output 1572.

In this example, add phase shift stage 1505 includes a beam splitter 1520a, which receives input signal 1560 and sends a first signal copy 1562a toward a first mirror 1530a, and a second signal copy 1564a toward a second mirror 1540a. First and second mirrors 1530a and 1540a reflect first and second signal copies 1562a and 1564a toward a second beam splitter 1550a. In this embodiment, second beam splitter 1550a combines components of the reflected first and second signal copies 1562a and 1564a to form output signals 1572a and 1574a.

Add phase stage 1510 is similar in structure and function to drop phase stage 1505. Add phase stage 1510 includes a beam splitter 1520b, which receives either signal 1574a being passed through from add phase stage 1505, or an added signal 1565. Beam splitter 1520b sends a first signal copy 1562b of the signal it receives toward a first mirror 1530b, and a second signal copy 1564b toward a second mirror 1540b. First and second mirrors 1530b and 1540a reflect first and second signal copies 1562b and 1564b toward a second beam splitter 1550b. In this embodiment, second beam splitter 1550b combines components of the reflected first and second signal copies 1562b and 1564b to form output signal 1576.

Some or all of mirrors 1530 and 1540 can comprise moveable mirror structures operable to vary their positions to result in a change in the length of the path of and phase difference between first and/or second signal copies 1562 and 1564. By varying the positions of mirrors 1530a and/or 1540a to switch between a phase

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difference of, for example, approximately zero and Pi, drop phase stage 1505 facilitates switching between passing input signal 1560 though stage 1505 and dropping signal 1560 from stage 1505. Similarly, by varying the positions of mirrors 1530b and/or 1540b to switch between a phase difference of, for example, approximately zero and Pi, drop phase stage 1505 facilitates outputting either pass through signal 1574, or added signal 1565 at output 1576.

pass-through embodiment shows this Although operation between stages over output 1574 and drop operation over port 1572, add/drop multiplexer could be reconfigured to communicate pass-through signals from port 1572 to port 1565 and drop signals from port 1574. In that embodiment, signals would pass through from the drop stage to the add stage at port 1572 where mirrors 1530a/1540a are positioned to provide a Pi phase shift, and would be dropped at port 1574 where those mirrors were positioned to provide no phase shift. Likewise, the input signal would pass through add stage to output 1576 where mirrors 1530b/1540b are positioned to create a Pi phase shift, whereas added signal 1565 would pass to output 1576 where those mirrors create no phase shift.

In operation, ADM 1500 receives input signal 1560 at beam splitter 1520a and communicates a first signal copy 1562a toward first mirror 1530a and a second signal copy 1564a toward second mirror 1540a. Mirrors 1530a and 1540a reflect first and second signal copies 1562a and 1564a toward beam splitter 1550a, which operates to combine components of those signals to generate an output signal. Depending on the position of mirrors 1530a

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and/or 1540a, drop phase shift stage 1505 will either pass input signal 1560 toward add phase shift stage 1510, or will drop input signal 1560 at output 1572, sending no signal to add phase shift stage 1510.

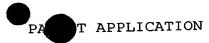
Add phase shift stage 1510 either receives pass through input signal 1574 from drop phase shift stage Mirrors 1530b 1505, or receives added signal 1565. and/or 1540b are then positioned to pass the received signal to output 1576. For example, in this embodiment if add phase shift stage 1510 receives a pass through signal 1574, mirrors 1530b and/or 1540b are positioned to introduce approximately no phase shift (or a multiple of 2Pi phase shift) between signal copies 1562b and 1564b to result in pass through signal 1574 being communicated through output 1576. On the other hand, if add phase shift stage instead receives added signal 1565, mirrors 1530b and/or 1540b are positioned to introduced an approximately Pi (or odd multiple of PI) phase shift between signal copies 1562b and 1564b to result in added signal 1565 being communicated through output 1576.

FIGURE 16d is a block diagram showing a plurality of add/drop multiplexers as shown in FIGURE 16b arranged to collectively form a wave division add/drop multiplexer 1600. In this example, each ADM of array 1610 is similar to that shown in FIGURE 16c. Of course, an array of add/drop multiplexers could likewise be formed from add/drop multiplexers such as those shown in FIGURE 16b.

In the illustrated embodiment, each drop phase shift stage includes two arms, at least one of which comprises a moveable mirror structure 1630a and/or 1640a. Mirrors 1630a and/or 1640a are operable to move in response to

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one or more control signals to result in a change in the length of the signal path and, therefore, a phase shift between signal copies communicated through the arms of the drop phase shift stages. Depending on the positions of mirrors 1630al-n and/or 1640al-n, wavelength signals 1660a-1660n can be selectively dropped or passed as inputs to the add phase shift stages.

Each add phase shift stage includes two arms, at least one of which comprises a moveable mirror structure 1630b and/or 1640b. Mirrors 1630b and/or 1640b are operable to move in response to one or more control signals to result in a change in the length of the signal path and, therefore, a phase shift between signal copies communicated through the arms of the drop phase shift stages. Depending on the positions of mirrors 1630b1-n and/or 1640b1-n, either pass though signals 1674 or added signals 1665 can be selectively communicated to outputs 1676.

Although the illustrated embodiment shows just one
20 MEMs device in each arm of each phase shifter stage,
additional MEMs devices could be implemented without
departing from the invention. Furthermore, although MEMs
devices 1630 and 1640 are shown at an approximately
forty-five degree grazing angle, these devices could be
located at other grazing angles to the signals being
reflected.

Using micro-electro-optic system (MEMS) based mirrors, such as those described with respect to FIGURES 3a-3c, provides an advantage of facilitating large scale replication of each add/drop stage. For example, each plurality of first mirrors 1530 could be simultaneously

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formed on a single semiconductor substrate. Likewise, could plurality of second 1540 mirrors semiconductor single formed on a simultaneously therefore, the invention, aspect of One substrate. facilitates construction of add/drop multiplexers capable processing numerous wavelengths small for add/drop single stage over a incremental cost This aspect of the invention provides multiplexer. significant cost savings in processing signals carrying information on multiple channels or wavelengths. 10

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FIGURE 17 is a flowchart showing examples of a method 1700 of facilitating optical add/drop multiplexing. Steps 1705 through 1730 describe a method 1702 applicable to both single phase shift solutions as well as embodiments using separate phase shift stages for add and drop operations.

In an embodiment using one phase shift stage to facilitate both pass-through operation and add/drop operation, the method 1700 begins at step 1705 where optical add/drop multiplexer (ADM) 1405 receives an optical input signal 1461. This may include, for example, receiving from a wave division multiplexer one wavelength of an optical signal at a beam splitter 1420. This may further include receiving an added signal 1465 at beam splitter 1420. ADM 1405 generates copies of the signals received by beam splitter 1420 at step 1710 and communicates, at step 1715, those copies toward first and second mirrors 1430 and 1440, respectively.

Depending on the desired function, ADM 1405 may position one or more of the mirrors to contribute to phase shift between the first and second signal copies.

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This may include, for example, one or both of mirrors 1430 and 1440 receiving control signals operable to cause move toward an inner a moveable mirror element to conductive layer.

Through the use of moving mirror elements, ADM 1405 can introduce a phase shift sufficient to either pass input signal 1461 transmitted output 1472, or to drop input signal 1461 in favor of added signal 1465, which will then be communicated from transmitted output 1472. For example, mirrors 1430 and/or 1440 can introduce no phase shift (or a multiple of 2 Pi)between the signal pass signal 1461 to causing input copies, transmitted output 1472 at step 1735. Alternatively, mirrors 1430 and/or 1440 can introduce a Pi (or odd multiple of Pi) phase shift at step 1725 to cause input signal 1461 to be dropped at output 1474. In that case, added signal 1465 is communicated as transmitted output 1472 at step 1730. Of course, the locations of input for input signal 1461 and added signal 1465 could be flipped without departing from the invention. In that case, a Pi (or odd multiple of Pi) phase difference would cause the input signal 1461 to be communicated at output 1472, zero (or 2Pi, or multiple of 2Pi) а while be signal 1465 to added difference would cause communicated as output 1472. 25

Steps 1705 through 1730 are also applicable to an embodiment using separate phase shift stages for the add In that case, the method 1700 and drop operations. begins at step 1705, where optical add/drop multiplexer (ADM) 1500 receives an optical input signal 1560. may include, for example, receiving from a wave division

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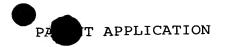
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multiplexer one wavelength of an optical signal at a beam splitter 1520a. ADM 1500 generates copies of that signal at step 1710 and communicates, at step 1715, the copies toward first and second mirrors 1530a and 1540a, respectively.

Depending on the desired signal processing function, ADM 1500 may position one or more of the mirrors to contribute to phase shift between the first and second signal copies at step 1720. This may include, for example, one or both of mirrors 1530a and 1540a receiving control signals operable to cause a moveable mirror element to move toward an inner conductive layer. ADM 1500 can introduce a phase shift sufficient to either pass input signal 1560 toward second stage 1510, or to drop input signal 1560 at output 1572, depending on the particular configuration being utilized.

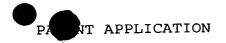
In the particular example shown in FIGURE 16b, mirrors 1530a and/or 1540a can introduce no phase shift (or a multiple of 2 Pi phase shift) between the signal copies, causing input signal 1560 to pass toward second phase 1510 at step 1735. Alternatively, mirrors 1530a and/or 1540a can introduce a Pi (or odd multiple of Pi) phase shift at step 1725 to cause input signal 1560 to be dropped at output 1572. In that case, an added signal 1565 is input to second stage 1510 at step 1730.

Regardless of whether the input signal 1560 is passed to second stage 1510 or whether added signal 1565 is introduced at second stage 1510, beam splitter 1520b of second stage 1510 generates copies of the signal received at step 1740. The signal copies are communicated to first and second mirrors 1530b and 1540b

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at step 1745. Again depending on the configuration and signal processing desired, ADM 1500 can positions one or more of the mirrors 1530b and/or 1540b to contribute to phase shift between the first and second signal copies. This may include, for example, one or both of mirrors 1530b and 1540b receiving control signals operable to cause a moveable mirror element to move toward an inner conductive layer.

and 1500 can introduce a phase shift sufficient to either pass input signal 1560 toward output 1576, or to pass added signal 1565 to output 1576. For example, mirrors 1530b and/or 1540b can introduce no phase shift (or a multiple of 2 Pi phase shift) between the signal copies, causing input signal 1560 to pass to output 1576 at step 1765. Alternatively, mirrors 1530b and/or 1540b can introduce Pi (or odd multiple of Pi) phase shift at step 1755 to cause added signal 1565 to be output at step 1760. Of course, the phase shifts discussed herein are for exemplary purposes only. Other configurations could use other phase shift combinations to achieve the desired signal processing consistent with the invention.

These steps can be duplicated at each add/drop multiplexer in an array of add/drop multiplexers to facilitate processing of any number of individual wavelength signals. This aspect of the invention provides a significant advantage in providing cost effective signal processing in multiple wavelength systems.

Although various aspects of the present invention 30 have been described in several embodiments, a myriad of changes, variations, alterations, transformations, and





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modifications may be suggested to one skilled in the art, and it is intended that the present invention encompass such changes, variations, alterations, transformations, and modifications as fall within the spirit and scope of the appended claims.